To: Walt Sanders[wsanders@vmgthehill.com]
From: McQueen, Jacqueline
Sent: Tue 2/3/2015 4:31:04 PM
Subject: Published journal article
Cheng et al Artifical Turf Review Supporting Into ES&T2014.pdf
Cheng et al Artifical Turf Review ES&T2014.pdf

Environmental Science & Technology

Critical Review

pubs.acs.org/est

Environmental and Health Impacts of Artificial Turf: A Review

Hefa Cheng,*,† Yuanan Hu,† and Martin Reinhard‡

†State Key Laboratory of Organic Geochemistry Guangzhou Institute of Geochemistry, Chinese Academy of Sciences Guangzhou 510640, China

‡Department of Civil and Environmental Engineering Stanford University Stanford, California 94305, United States

* Supporting Information

With significant water savings and low maintenance requirements, artificial turf is increasingly promoted as a replacement for natural grass on athletic fields and lawns. However, there remains the question of whether it is an environmentally friendly alternative to natural grass. The major concerns stem from the infill material that is typically derived from scrap tires. Tire rubber crumb contains a range of organic contaminants and heavy metals that can volatilize into the air and/or leach into the percolating rainwater, thereby posing a potential risk to the environment and human health. A limited number of studies have shown that the concentrations of volatile and semivolatile organic compounds in the air above artificial turf fields were typically not higher than the local background, while the concentrations of heavy metals and organic contaminants in the field drainages were generally below the respective regulatory limits. Health risk assessment studies suggested that users of artificial turf fields, even professional athletes, were not exposed to elevated risks. Preliminary life cycle assessment suggested that the environmental impacts of artificial turf fields were lower than equivalent grass fields. Areas that need further research to better understand and mitigate the potential negative environmental impacts of artificial turf are identified.

INTRODUCTION

Artificial turf (also referred to as synthetic turf) is a surfacing material engineered to mimic the appearance and sports performance (e.g., shock absorption, energy restitution, vertical deformation, slide and slip resistance, and wear resistance) of natural grass on athletic fields, golf courses, and lawns. The first generation artificial turf made of short-pile plastic fibers was introduced in the 1960s. The improved second generation products featuring sand infill between the fibers made artificial turf widely popular in the early 1980s. The third generation artificial turf introduced in the late 1990s is infilled with crumb rubber or a mixture of sand and crumb rubber to keep the plastic fibers upright and provide shock absorption similar to that of natural grass. The new generation of products have been accepted as providing improved safety, playability, appearance, durability, with lower annual operating costs and maintenance requirements, and have moved rapidly beyond athletic fields to residential lawns and landscaping.[1] Artificial turf is now widely considered as an ideal replacement for grass playing surface in cases where natural grass cannot grow, or where maintenance of natural grass is expensive or undesired. The advantages and limitations of artificial turf compared with natural grass are summarized in Table 1.

The third generation artificial turf system is typically composed of three primary layers (Figure 1a): (a) artificial grass fibers (polyethylene, nylon, or a blend of polyethylene and nylon); (b) infill (rubber made from one or more sources, or a mixture of sand and rubber); and (c) carpet backing (a blend of polypropylene, polyamide 6, polyolefins, and/or polyurethane). The rubber infill is produced predominantly by mechanical disintegration of scrap tires, and recycled athletic shoes in rare cases. Rubber manufactured specifically for infill purposes is also available, although crumb rubber produced from scrap tires is much cheaper compared to virgin rubber ($0.04−0.30 vs $1.00 or more per pound, price in early 2000s).[2] Significant amount of scrap tires can be recycled by artificial turf products: tire rubber crumb is applied at up to 6 lbs/ft^2 in most artificial turf fields (some "heavyweight" infill systems even contain 9.2 lbs/ft^2),[3] while 1−2 lbs/ft^2 of tire rubber crumb is often used in lawns. Sand is also used as an infill material in some artificial turf products to improve the hardness, and those with rubber/sand infill generally cost less and perform most like natural grass. Unlike grass lawns that can often become waterlogged during the rainy season, artificial turf fields are constructed with a built-in drainage system (Figure 1b) that allows water to drain quickly after the rain.

Received: October 3, 2013
Revised: December 15, 2013
Accepted: January 27, 2014
Published: January 27, 2014

Table 1. Comparison of the Benefits and Disadvantages of Natural Grass and Artificial Turf

	natural grass	artificial turf
cost	the installation cost of grass fields is low, but the annual maintenance cost is high.	the installation cost of artificial turf fields is quite high, while the annual maintenance cost is rather low; the increased practice and play time, as well as the flexibility of the artificial turf fields to be used for multiple events make the per use cost of artificial turf fields much lower than that of grass fields.[62]
visual appearance and smell	the visual appearance and smell of grass fields are pleasing, but proper maintenance is required; growth of natural grass is strongly influenced by drought and cold.	artificial turf is often virtually indistinguishable from natural grass when viewed from a distance; artificial turf stays green all year without requiring maintenance, although the color may fade over time; the tire rubber crumb in artificial turf can heat up and emit an unpleasant smell under direct sunlight.
durability	natural grass cannot sustain excessive wear and tear; grass fields need to "rest" after heavy uses for the grass to recover.	artificial turf stands up to heavy use without compromising the quality of play caused by damage of the surface from over use; artificial turf fields always stay uniform and consistent; artificial turf fields can be utilized with virtually no "rest" required.
installation conditions	natural grass cannot grow well in desert areas and extremely cold climates; due to lack of sunlight, growing natural grass in indoor sports stadiums and arenas is challenging and expensive.	artificial turf can be installed in virtually any environment.
field availability	the playable time allowed by grass fields is typically no more than 20 h/week, or 680 h/year for three seasons.	artificial turf is well suited for multipurpose fields and can host a range of sporting activities including football, soccer, lacrosse, baseball, and softball, which means more practice and game time; one artificial turf field can typically accommodate the play of 3–4 natural grass fields, and the playability (hours of use) of artificial turf fields can be up to 7.7 times of that of natural grass fields.[6] artificial turf fields allow up to approximately 3000 h of playing time annually.[1,6,62]
drainage	grass fields frequently become water logged during the rainy season, which exacerbates damage to the surfaces and limits play thereon.	artificial turf fields have excellent drainage property because of their totally porous nature and the built-in drainage system, and can be used immediately after rainfalls.
irrigation requirement	natural grass requires large amount of irrigation water. A full-size grass sports field in the U.S. generally consumes 0.5 to 1 million gallons of water each year.[5,6]	artificial turf essentially requires no irrigation; artificial turf fields may need to be irrigated to cool and clean the playing surface on hot summer days.
maintenance	natural grass fields require frequent maintenance, including watering, mowing, fertilizing, and periodic reseeding; fossil fuels, chemicals, fertilizers, and herbicides, which produce greenhouse gas (GHG) emissions when manufactured, are required for growing and maintaining turf grass; the requirement of equipments, fertilizers, chemicals, and water makes the additional cost of maintenance quite high.	artificial turf fields need little maintenance: only occasional sanitation, raking, cleaning, and vacuuming are required; artificial turf fields eliminate the use of chemicals, which can cause soil and groundwater contamination.
player safety	natural grass athletic fields have been used successfully for many years; the presence of holes or mounds made by moles, gophers, or other animals, and slippery mud areas can increase the chance of player injuries.	artificial turf is generally regarded as being as safe to play on as typical grass surfaces;[99,100] studies consistently indicated that the incidence and severity of athlete injuries on the third generation artificial turf are similar to, or better than those on natural grass;[99,101−103] artificial turf fields are free of gopher holes, bumps, or muddy patches inherent in grass fields.
environmental functions	natural grass reduces surface temperatures, lowers noise levels, traps and biodegrades airborne pollutants, supports worms and insects that are fed on by birds and other animals;[104] due to natural grasses' ability to store atmospheric CO_2 in the soil as organic carbon, grass fields have a net negative carbon footprint, although the constant maintenance activity on sports fields can expose the organic carbon to air, which offsets the actual carbon sequestration of grass fields;[105] natural grasses emit photochemically reactive VOCs, especially during and after mowing, which is related to plant growth, maintenance, and wound defense mechanisms.[106,107]	artificial turf may cause environmental damage, including consumption of raw materials and energy, and emissions to air, water, and land; due to the lack of transpiration and heat trapping in the plastic and rubber materials, the surface temperature of artificial turf is elevated (20 °C or even more above that of natural grass) under direct sunlight;[47,48] production and transportation of artificial turf release large amounts of GHGs; artificial turf needs to be disposed of in landfills at the end of its functional life as most of the components cannot be recycled.

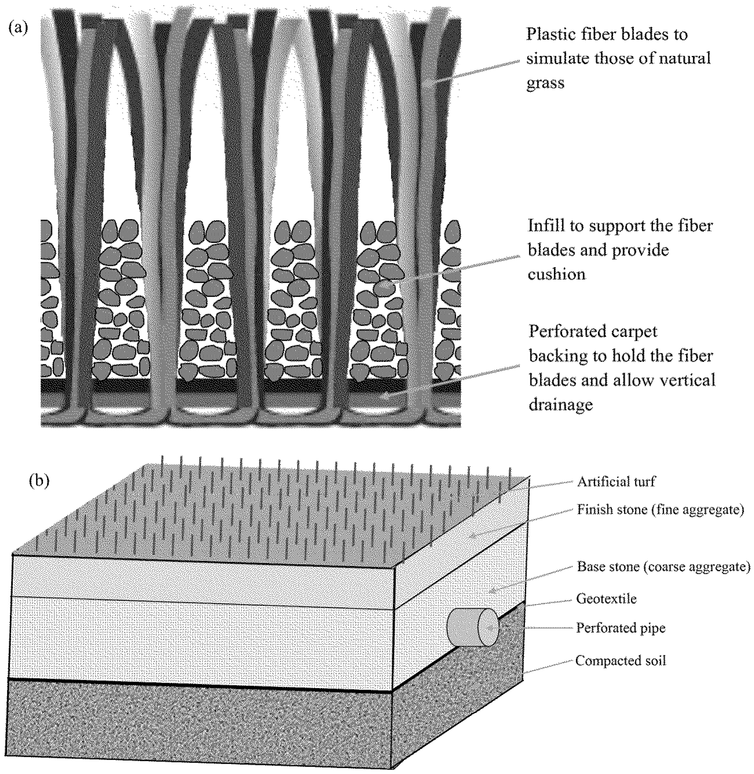

Figure 1. Schematic illustrations of the makeup of a typical artificial turf field: (a) the major components of artificial turf, and (b) the built-in drainage system.

Manufacturers typically emphasize that artificial turf is environmentally friendly with the use of recycled tire rubber. Because of their large production volume and durability, the disposal of scrap tires is a major challenge for waste management, and a truly environmentally friendly disposal method remains to be found (Supporting Information, SI). Artificial turf can reuse large amounts of scrap tires: an average soccer pitch/field of artificial turf contains approximately 100 tonnes of tire rubber crumb. It has been estimated that 26.2% of the scrap tires generated in the U.S. were recycled into tire rubber crumb, with about 0.18 million tonnes used in sports surfacing in 2009.[4]

Today artificial turf is being widely promoted as a cost-efficient, environmentally- and user-friendly product that can replace natural grass on sports fields and residential lawns. The markets for artificial turf in the U.S. and Europe are both over one billion dollars, and continue to grow, while manufacturers of artificial turf have also begun to pay more attention to the emerging markets, such as China. Depending on the region in the U.S., a full-size artificial turf sports field can result in an annual savings of 0.5 to 1 million gallons of water.[5,6] Recognizing the significant water conservation potential, many cities and water conservation institutions in the dry regions of the U.S. have begun to offer financial incentives for the replacement of residential lawns with artificial turf. It has been claimed that the use of artificial turf conserved about 5 billion gallons of water in the U.S. in 2011.[5]

In spite of the obvious environmental benefits, such as saving water, requiring no fertilizer or pesticide, and reusing rubber from scrap tires, artificial turf can pose potential risk to human health and the environment, primarily from the contaminants released by the tire rubber crumb infill. These emissions and their potential impacts have not received much attention until recently.[7−10] The key question that needs to be answered is whether artificial turf is a truly "green" alternative to natural grass. This review summarizes the benefits of artificial turf, assesses its major environmental and health impacts, and identifies research that is needed to ascertain and mitigate the environmental impacts of artificial turf. Available data were compiled from published journal articles, conference proceedings, books, and gray literature. The latter includes technical reports published by governmental agencies, academic institutions, trade publications, and information gathered from Web sites of manufacturers and other groups, which are typically not subjected to peer-review and might thus contain data that were collected to represent biased viewpoints. Although some cited reports came directly or indirectly from industries with a financial interest in promoting artificial turf, data were cross-checked with other sources to ensure the validity of the conclusions as much as possible.

ASSESSING THE ENVIRONMENTAL IMPACTS OF ARTIFICIAL TURF

The use of recycled tire rubber significantly reduces the cost of artificial turf, although this practice is afflicted with potential downsides, as tire rubber contains a range of chemical vulcanizers, oil-based plasticizers, antioxidants, antiozonants, and fillers in the blend of natural and synthetic rubber,[11−16] which are summarized in the SI. Despite the common assumption that tire rubber is extremely resistant to environmental breakdown, organic compounds and heavy metals in the rubber matrix can be slowly released through volatilization and/or leaching under natural conditions. Shredded tires in various conditions from tire chips to finely ground rubber crumb have been used in a range of civil engineering applications, such as lightweight fill for embankments and retaining walls, insulation blocks, drainage aggregates, surface materials for playgrounds and racetracks, soil amendments, and surface mulches.[37] A large number of studies have characterized the environmental impacts associated with such direct reuse of scrap tire materials, which provide important insights on the potential environmental impacts associated with artificial turf.

Volatilization of Organic Contaminants. The odor of tires is characteristic of amines and sulfur-containing organic compounds (with very low odor thresholds) that are used in the compounding of tire rubber.[11,16] Despite the unpleasant smell, car and truck tires do not release significant amounts of volatile organic compounds (VOCs) or semivolatile organic compounds (SVOCs) under ambient conditions and are not commonly considered as a source of air pollution. In contrast, hundreds of VOCs and SVOCs have been identified in the off-gases of rubber vulcanization and pyrolysis.[15,17,18] The levels of total VOCs in the air of two tire shredding facilities located in central Taiwan ranged from 1.4 to 2.2 ppm, which were not significantly different from the local background level (~1.4 ppm).[19] Chemical analysis indicated the presence of various groups of air pollutants, such as aliphatics (e.g., octane, decane, and undecane), aromatics (e.g., benzene, toluene, ethylbenzene, and xylenes), polycyclic aromatic hydrocarbons (PAHs), methyl isobutyl ketone, styrene, and benzothiazole.[19] These contaminants probably resulted from the decomposition of rubber polymers, vulcanization accelerators, and plasticizers during tire shredding and grinding. It has been reported that benzothiazole was the most abundant volatile compound in the vapor phase over tire rubber crumb, and that the concentrations of VOCs leveled off significantly within 2 weeks under natural weathering conditions and became relatively constant thereafter.[8]

Leaching of Heavy Metals and Organic Contaminants. Whole tires and laminated tires have long been used as dock bumpers and fenders against heavy rubbing and pushing forces of vessels with few concerns raised about their impact on water quality. However, the much smaller tire chips and rubber crumb may release heavy metals and organic contaminants more readily, and thus present a risk to aquatic environment. Results of toxicity characterization leaching procedure (TCLP) analyses (SI Table S1) showed that the regulated metals (As, Ag, Ba, Cd, Cr, Hg, Pb, and Se) and organic contaminants were typically below their respective regulatory limits in the leachate of tire rubber in various shapes.[20−23] A wide range of organic contaminants (SI Table S2) have been detected at very low concentrations in the leachate of tire shreds and chips, which resulted from the breakdown of natural and synthetic rubber polymers, compounds associated with the carbon black, and various additives such as plasticizers and accelerators.[13,15,24−30] Tire rubber leachate typically also contained elevated levels of Zn, while other heavy metals, such as Cd, Cr, Cu, Fe, Mg, and Mn were often present at relatively low concentrations.[7,8,15,21,24,25,28−35] These metals originated primarily from the metal oxides and residual steel belt wires of the tire shreds and chips (SI Tables S3 and S4). Laboratory studies found that acidic and alkaline conditions favored the leaching of metals and organic compounds from tire rubber crumb, respectively, and the leaching rates increased with decreasing particle size.[23,31] A number of field studies have been conducted to investigate the impact of tire shreds and chips used in civil engineering applications on the quality of surface water and groundwater through sampling of existing sites and field trials with follow-up monitoring of up to 2 years.[21,27,29−31,36,37] In general, Fe, Mn, Zn, and Al appeared to be the major contaminants of concern even though their concentrations did not exceed the respective maximum contaminant levels (MCLs) for drinking water in most cases, while the organic contaminants (e.g., amines, aniline, quinoline, amides, and benzothiazole) occurred only at trace levels. These results suggest that scrap tire materials may affect surface water and/or groundwater, and warrant further field study with controls.

The ecotoxicity of tire rubber leachate has long been recognized, although determination of the specific hazardous substances responsible for the toxic effects was difficult. Lethal and sublethal effects on aquatic biota as well as genotoxicity have been documented for tire leachate and solvent extracts of tire rubber.[12−15,19,25,26,38−43] Leachate from used tires was also found to be more toxic than that from the new ones,[14] which could be explained by the easier release of hazardous substances from the matrix of worn rubber. In general, the major toxic constituent in tire leachate is zinc, with minor contributions from organic compounds. Even though leachate from tire chips and tire rubber crumb can be toxic to some aquatic life, dilution (i.e., by infiltrating rainwater and groundwater) in natural systems is expected to reduce its toxicity and lower the associated ecological risk.

Contaminants Contributed by the Nonrubber Components of Artificial Turf. Besides tire rubber crumb, plastic fibers of artificial turf are also a potential source of heavy metals, particularly lead. Some manufacturers produced plastic fibers with encapsulated lead chromate pigment in the early years of artificial turf product development. Excessive levels (several mg/g) of lead had been found in some artificial turf fibers made of nylon or polyethylene/nylon blends, while fibers made of polyethylene commonly contained very low or undetectable levels of lead.[10,44,45] Even though the leaded pigment particles are not expected to leach from intact nylon fibers, deterioration of these fibers over time can result in the formation of lead-containing dust. In addition, artificial turf fields with exotic colors could also contain elevated levels of lead, probably due to the use of specialty pigments.[45] A scoping-level field monitoring study found that the lead contents in the fibers of six artificial turf fields ranged from 0.002 to 0.39 mg/g, which were below the standard set by the U.S. Environmental Protection Agency (USEPA) for lead in soils (0.40 mg/g).[46] Only fibers from the repaired area of one field had a high level of lead (0.70 mg/g), while the lead contents of tire rubber crumb in these fields only ranged from 0.01 to 0.05 mg/g.[46]

A comprehensive laboratory investigation found that the fibers from two artificial turf manufacturers had relatively high levels of Al (1.2−2.1 mg/g) and Fe (2.7−4.0 mg/g), while the contents of Cr, Cu, Mg, Mn, Ni, Sn, and Ti were in the range of 0.01−1 mg/g and those of Ba, Co, Mo, Pb, and Sr were below 0.01 mg/g.[35] The fibers from a third manufacturer contained even higher levels of Fe (14.3 mg/g) and Zn (7.6 mg/g), and relatively high levels of Ti, Sn, Cu, Co, and Ni (0.1−1 mg/g) as well.[35] The relatively high levels of heavy metals probably came from the coloring pigments and UV inhibitors (for photo-resistance) in the polymers. The heavy metal contents of the carpet backing materials from these artificial turf products were

dx.doi.org/10.1021/es4044193 | Environ. Sci. Technol. 2014, 48, 2114−2129

Table 2. Concentration Ranges of Heavy Metals and Organic Contaminants Detected in the Drainage from Artificial Turf Fields

study and contaminants measured	sampling site and sampling method	concentration	water quality standard
Moretto (2007)[52]			
zinc	A newly installed artificial turf football pitch (with tire rubber crumb infill) located in the Lyon region of France was sampled. Field drainage was collected using a lysimetric system made from a stainless steel sheet buried under the field. The monitoring period was 11 months.	0.074–0.488 mg/L	5 mg/L[a]
arsenic		0.001–0.0147 mg/L	10 μg/L[b]; 10 μg/L[c]
copper		0–0.011 mg/L	1.3 mg/L[b]; 1.0 mg/L[a]; 2 mg/L[c]
lead		0–0.014 mg/L	0.015 mg/L[b]; 10 μg/L[c]
sum of benzo(k)fluoranthene, fluoranthene, benzo(b)fluoranthene, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, and benzo(g,h,i)perylene.		0.016–0.091 μg/L	
Bristol and McDermott (2008)[50]			
zinc	Three artificial turf fields (with tire rubber crumb infill) located in the state of Connecticut in the U.S. were sampled. One of these fields was installed in the year of sampling, while the others were constructed in the previous year. Grab samples of the drainage were obtained from the discharge pipes of these fields.	<0.002–0.036 mg/L	5 mg/L[a]
lead		<0.001 mg/L	0.015 mg/L[b]; 10 μg/L[c]
selenium		<0.002 mg/L	50 μg/L[b]; 40 μg/L[c]
cadmium		<0.001 mg/L	5 μg/L[b]; 3 μg/L[c]
Hofstra (2008)[68,72]			
zinc	A total of five artificial turf fields (with tire rubber infill) from 5 to 6 years old in Sittard, Netherlands were sampled. Drainage from these fields was collected.	mean: 0.016 mg/L	5 mg/L[a]
Lim and Walker (2009)[47]			
antimony	A one-year old artificial turf field in New York city of the U.S. was sampled. Only surface runoff was collected, while the volume of runoff from the drainage collection pipes was insufficient.	<2.3 μg/L	6 μg/L[b]; 20 μg/L[c]
arsenic		<1.8 μg/L	10 μg/L[b]; 10 μg/L[c]
beryllium		<0.096 μg/L	4 μg/L[b]
cadmium		<0.35 μg/L	5 μg/L[b]; 3 μg/L[c]
chromium		2.2 μg/L	100 μg/L[b]
copper		5.4 μg/L	1.3 mg/L[b]; 1.0 mg/L[a]; 2 mg/L[c]
lead		1.7 μg/L	0.015 mg/L[b]; 10 μg/L[c]
mercury		<0.13 μg/L	2 μg/L[b]; 6 μg/L[c]
nickel		8.8 μg/L	30 μg/L[c]; 7 μg/L[c]
selenium		<1.9 μg/L	50 μg/L[b]; 40 μg/L[c]
silver		<0.54 μg/L	0.1 mg/L[a]
thallium		<1.9 μg/L	2 μg/L[b]
zinc		59.5 μg/L	5 mg/L[a]
30 VOCs		<1 μg/L each	
56 SVOCs		<5–10 μg/L each	

dx.doi.org/10.1021/es4044193 | Environ. Sci. Technol. 2014, 48, 2114–2129

Table 2. continued

study and contaminants measured	sampling site and sampling method	concentration	water quality standard
Cheng and Reinhard (2010)[35]			
zinc	A one-year old artificial turf field (with tire rubber infill) in northern California of the U.S. was sampled. Drainage was collected using lysimetric systems made from plastic funnels buried under the field. The monitoring period was 1 month.	0.129–0.473 mg/L	5 mg/L[a]
nickel		<0.001–0.009 mg/L	30 μg/L[c]; 7 μg/L[c]
manganese		0.007–0.011 mg/L	0.05 mg/L[a]
iron		0.003–0.114 mg/L	0.3 mg/L[a]
copper		0.001–0.034 mg/L	1.3 mg/L[b]; 1.0 mg/L[a]; 2 mg/L[c]
cobalt		0.002–0.007 mg/L	
barium		0.010–0.043 mg/L	2.0 mg/L[b]; 0.7 mg/L[c]
naphthalene		<0.002 μg/L	
acenaphthylene		<0.002–0.314 μg/L	
acenaphthene		0.009–0.023 μg/L	
fluorene		<0.002 μg/L	
phenanthrene		0.071–0.292 μg/L	
anthracene		0.028–0.390 μg/L	
fluoranthene		0.029–0.180 μg/L	
pyrene		<0.002–0.02 μg/L	
benzo[a]anthracene		<0.002–0.212 μg/L	
chrysene		<0.002–0.034 μg/L	
benzo[b]fluoranthene		<0.002–0.040 μg/L	
benzo[k]fluoranthene		<0.002–0.014 μg/L	
benzo[a]pyrene		<0.002 μg/L	0.2 μg/L[b]; 0.7 μg/L[c]
indeno[1,2,3-cd]pyrene		<0.002 μg/L	
dibenz[a,h]anthracene		<0.002 μg/L	
benzo[g,h,i]perylene		<0.002 μg/L	
sum of 16 EPA priority PAHs		0.12–0.95 μg/L	

[a]National Secondary Drinking Water Regulations of USEPA. [b]National Primary Drinking Water Standards of USEPA. [c]Current guideline value of the World Health Organization.

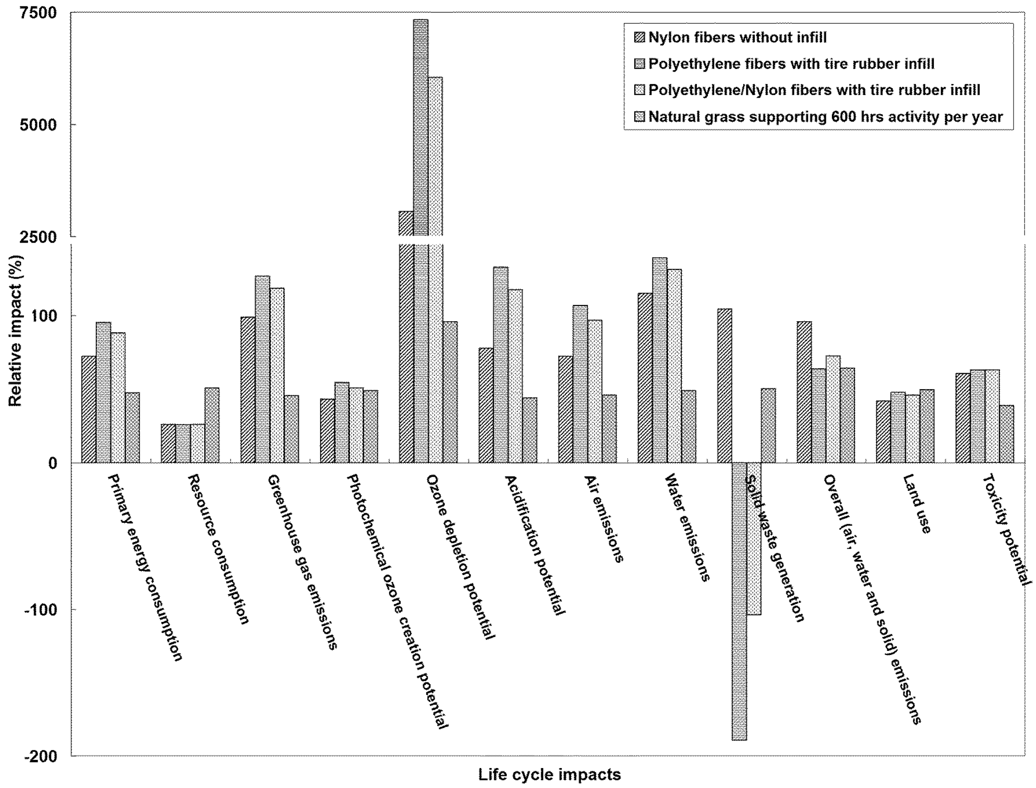

Figure 2. Life cycle environmental impacts of three representative artificial turf fields and an equivalent grass field (75 000 ft^2) that supports 600 h of activity per year, using a grass field of the same size but with an annual availability of 300 h as the basis of comparison (data from ref 62). One artificial turf had nylon fibers without infill, while the others had tire rubber crumb infill but with fibers made of polyethylene and 70% polyethylene/30% nylon, respectively. Although artificial turf fields could support up to 3000 h of activity per year, they were assumed to have annual availability of 600 h in this comparison. For natural grass fields, 300 h event activity per year is the typical annual playing capacity, while 600 h activity/year is the upper limit.

generally comparable to or less than those in the fibers.[35] Lead contents in the fibers and carpet backing materials were quite low (close or below 0.001 mg/g), indicating it was not a common additive used in the production of current generation of artificial turf. The fibers and carpet backing of artificial turf are made from the same polymers used in the manufacturing of a wide range of consumer products, and are not expected to have significant adverse environmental impacts. Nonetheless, the use of encapsulated lead chromate in some old fields and specialty colorants in fields with exotic colors makes it necessary to assess the fibers of artificial turf fields on a case-by-case basis.

Observations from Artificial Turf Fields. The tire chips or rubber crumb used in various civil engineering applications can be buried in soils, above or below the groundwater table, or stay at the surface. In contrast, the tire rubber crumb is applied as a relatively thin layer on the surface of artificial turf fields, and the sizes are typically much finer than the scrap tire materials used in civil engineering applications. Therefore, field observations are essential for understanding the actual release of hazardous substances from artificial turf and the potential impacts on the environment and human health.

The impact of artificial turf on the air quality of sports fields has been closely monitored in a number of studies. In general, the levels of VOCs, SVOCs, PAHs, heavy metals, and particulates ($PM_{2.5}$ and PM_{10}) in the air above outdoor artificial turf fields were found to be comparable to those of local background, and were within the regulatory limits,[9,46−51] although the results might only be applicable to the specific fields and conditions measured. One study found that the levels of PM_{10} and metals at the high play activity sites of artificial turf fields, although elevated compared to the background concentrations, were below the corresponding air quality standards.[46] The VOCs and SVOCs in the air above outdoor artificial turf fields resulted from volatilization from the fields and local traffic emissions, both of which were subject to air dispersion and dilution. In contrast, the concentrations of VOCs and PAHs measured in indoor sports halls with artificial turf were slightly elevated,[52−54] while the levels of particulates were similar to those in other urban indoor settings.[53,55]

With the porous structure of artificial turf, precipitation can easily percolate through the infill layer and potentially leach heavy metals and organic contaminants out of the tire rubber crumb. Several studies have characterized the contaminants in the drainage of artificial turf fields (Table 2). Overall, the concentrations of heavy metals and organic contaminants in the drainage were low with the exception of Zn, which occurred at concentrations up to near 0.5 mg/L. Many studies have demonstrated the removal of various heavy metals (such as Cu, Cd, Pb, and Hg) and organic contaminants (e.g., xylenes, toluene, naphthalene, and trichloroethylene) from wastewaters by tire rubber crumb,[56−59] while some of them also observed that zinc concentrations became elevated despite the removal of other heavy metal ions.[56,59] Relative to rainwater, the tire rubber crumb in artificial turf is expected to function as a net source of heavy metals and organic contaminants instead of a sink.

Ecotoxicity can be expected for the drainage from artificial turf fields with elevated levels of Zn, which adversely affects the growth, survival, and reproduction of aquatic plants, protozoans, sponges, molluscs, crustaceans, echinoderms, fish, and amphibians at concentrations as low as 10−25 μg/L.[60] The drainage from four pilot setups (with tire rubber crumb and specialty synthetic rubber infills) with controlled atmosphere and supervised human intervention treated with simulated rain showed very slight toxicity to Daphnia magna and Pseudokirchneriella subcapitata, while the drainage from an artificial turf football pitch (with tire rubber crumb infill) showed essentially no toxicity.[52] One field sample did show a low impact on the aquatic species, but chemical analysis results suggested that it was probably due to pollution external to the field.[52] Another study also found that the drainage from an artificial turf field with tire rubber crumb infill exhibited no toxicity to Daphnia pulex.[50]

Although air and water quality monitoring had been conducted on artificial turf fields of various ages (from newly constructed to 6 years old or more), the numbers of fields sampled and samples collected at each site were rather limited. Thus the results may not necessarily represent the potentially large variations in the design, manufacturing material, geographical location, use pattern, age, and other conditions of artificial turf fields, which can affect the release of contaminants. In addition, these field investigations were often constrained by available resources (e.g., personnel, equipment, and budget) and accessibility of field sites. Even though the existing field studies indicate artificial turf fields have limited impacts on air quality and aquatic environment, more comprehensive field monitoring data are needed to verify these findings.

Results from Preliminary Life Cycle Assessment (LCA) Studies. Both artificial turf and natural grass can have a range of environmental impacts, including consumption of raw materials and energy, and emissions to air, water, and land. Therefore, determination of which type of product has a lower overall environmental burden is not straightforward. To this end, LCA provides an efficient tool for systematically comparing the environmental impacts of artificial turf and natural grass through all stages of their life cycles (i.e., from "cradle to grave").

Constructed mostly from synthetic materials, artificial turf fields have a much larger carbon footprint compared to grass fields. It has been estimated that the total greenhouse gas (GHG) emissions from manufacturing, transporting, installing, maintaining, and disposing of a 9000 m^2 artificial turf field in Toronto, Canada over a 10 year period is 55.6 tonnes CO_{2e}, while that from construction and maintenance of a grass field of the same size is −16.9 tonnes CO_{2e}.[61] Through absorbing large quantity of CO_2 during growth, natural grass serves as a carbon sink. On the other hand, the GHG emissions from the artificial turf field would be nearly doubled if the components were not recycled at the end of life.[61] It is worth pointing out that these results are site specific (SI) and the differences in playable time of the two types of fields are not accounted for in the comparison.

Figure 2 compares the life cycle environmental impacts of three representative artificial turf products with those of natural grass on a multipurpose recreational sports field (75 000 ft^2) over a 20-year time frame. Field availability, durability of the artificial turf fields, and maintenance requirement of the grass fields were based on the average data in the U.S.[62] The results indicate that artificial turf performed better or comparable to natural grass in the major environmental categories, including energy and resource consumption, emissions (air, water, and solid waste), toxicity potential, and land uses over the production, use, and disposal phases. Although the ozone depletion potential of the artificial turf fields, which stemmed predominantly from production and transportation, was much higher than that of grass fields, its contribution to the overall environmental impacts was less than 1% over their life cycles.[62]

The actual environmental impacts of natural grass and artificial turf fields are strongly dependent on their availability. For the grass field, its environmental impacts could almost all (excluding the ozone depletion potential) be reduced by a half with the doubling of field availability (Figure 2). Artificial turf fields have much higher playability compared to grass turf fields because of the lower maintenance requirement, superior durability, and availability in all weather conditions.[51] To have the same hours of use (e.g., 2400 h), additional grass fields (which are still not playable during the rainy season) have to be built to match the availability of an artificial turf field, which would involve significant environmental impacts from the construction and maintenance activities.[6] Therefore, the environmental impacts of artificial turf fields relative to grass fields can be significantly reduced when they are used toward the maximum availability (i.e., by substituting multiple grass fields).

It should be noted that the results of LCA are model-based representations of the real environmental impacts for the specific turf fields, and are only valid under the specific assumptions made on their production, installation, use, maintenance, and disposal (SI). The environmental and health impacts of a product can be significantly influenced by the material and energy inputs and outputs considered for each stage of its life cycle, as well as limitations in data and knowledge of specific environmental impacts.[63,64] The LCA studies conducted to date have limited scopes and are far from comprehensive or representative of all types of artificial turf and natural grass fields in all geographical conditions. Cooperation and participation of the artificial turf industry by sharing relevant data, and monitoring data on the emissions of organic contaminants and heavy metals to air, water, and land during the functional lifetimes of artificial turf fields, which were not included in previous studies, will be crucial in more accurately tracking their life cycle environmental impacts in the future.

HUMAN HEALTH IMPACT OF ARTIFICIAL TURF FIELDS

Because tire rubber crumb contains a wide range of toxic and even carcinogenic chemicals that can be released into the surrounding environment, the potential health risk for field users has been a major concern. Players can be exposed to the rubber particles and their hazardous constituents through several routes, including ingestion, dermal uptake, and inhalation, as illustrated in Figure 3. Many risk assessment studies have been conducted to characterize the health risk of tire rubber crumb in artificial turf fields via these exposure routes, with the results consistently showing that no significant health risk was associated with being on or playing on such fields.

dx.doi.org/10.1021/es4044193 | Environ. Sci. Technol. 2014, 48, 2114−2129

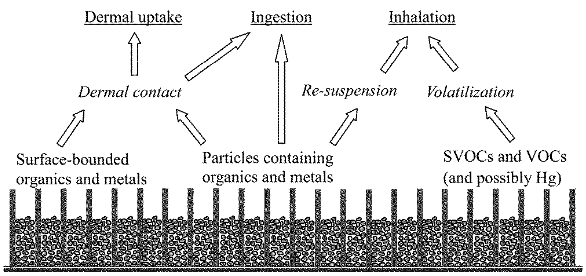

Figure 3. Major exposure pathways for athletes and occasional users to the hazardous substances in artificial turf fields. Tire rubber crumb can be intentionally or incidentally ingested by the field users, particularly children. SVOCs and VOCs volatilized from the tire rubber crumb and the fine particulates resuspended from the field can be inhaled. The organic contaminants and heavy metals on the exterior surfaces of the fiber blades and rubber infill, as well as the fine rubber granules, can stick to the skin and clothes upon contact. As a result, the users can also be exposed to these substances through dermal uptake and incidental ingestion (e.g., via hand-to-mouth activity).

Although intentional or incidental oral ingestion of tire rubber crumb on artificial turf fields is not a major exposure pathway for typical users, this may happen for young children. The potential risk of direct ingestion had been assessed in many studies, and no significant acute, cancer, or chronic adverse health effects were found at exposure levels ranging from acute to chronic scenarios.[43,54,65−69] Oral exposure can also occur through hand-to-mouth activity following contact with artificial turf surfaces, and such risk is typically associated with high degree of variability and uncertainty as the exposure is influenced by many factors, including the frequencies of field use, hand-to-playground contact, and hand-to-mouth activity, as well as the transfer efficiencies of chemicals from hand to mouth.[55] Nonetheless, there is no indication that the exposure to hazardous substances (PAHs and Pb) in tire rubber crumb via hand-to-mouth contact could cause adverse health effects.[65,70,71] Overall, studies evaluating end points in both children and adults consistently found that the tire rubber crumb in playgrounds and artificial turf fields poses low risk to human health through oral exposure.

Players can be exposed to the chemicals leached from the components of artificial turf and the tire rubber crumb through skin absorption. However, with the natural protection offered by human skin and the typically short contacting time with tire rubber crumb, dermal uptake of chemicals is unlikely to cause systemic toxicity.[55] In fact, risk assessment studies have shown that the doses of toxic chemicals exposed through dermal absorption were too low to cause any adverse health effects, including allergic response or indicated sensitization, for children and adults playing on artificial turf fields.[54,65,67] Biological monitoring also revealed that the level of a biomarker (1-hydroxypyrene) for PAH exposure in the urines of adult football players did not increase after intensive skin contact with rubber crumb on artificial turf fields, suggesting the uptake of PAHs via dermal pathway (and other exposure pathways as well) was negligible.[68,72]

Inhalation of VOCs, SVOCs, and particulates/dusts released from the tire rubber crumb of artificial turf fields is another important exposure pathway, particularly given the accelerated inhalation rates of the players.[48] Field monitoring showed that the levels of PAHs and VOCs detected in the air above outdoor artificial turf fields were not high enough to threaten human health,[47,48,73] and that the health risk from indoor artificial turf was also below the level of concern with adequate facility ventilation.[52−54] One study found that the PAH emissions from artificial turf fields could result in an excess lifetime cancer risk of 1×10^{-6} for professional athletes with 30 years of intense activity (5 h/day, 5 days/week, all year round) from inhalation, but no risk for discontinuous or amateur users.[9] No elevated

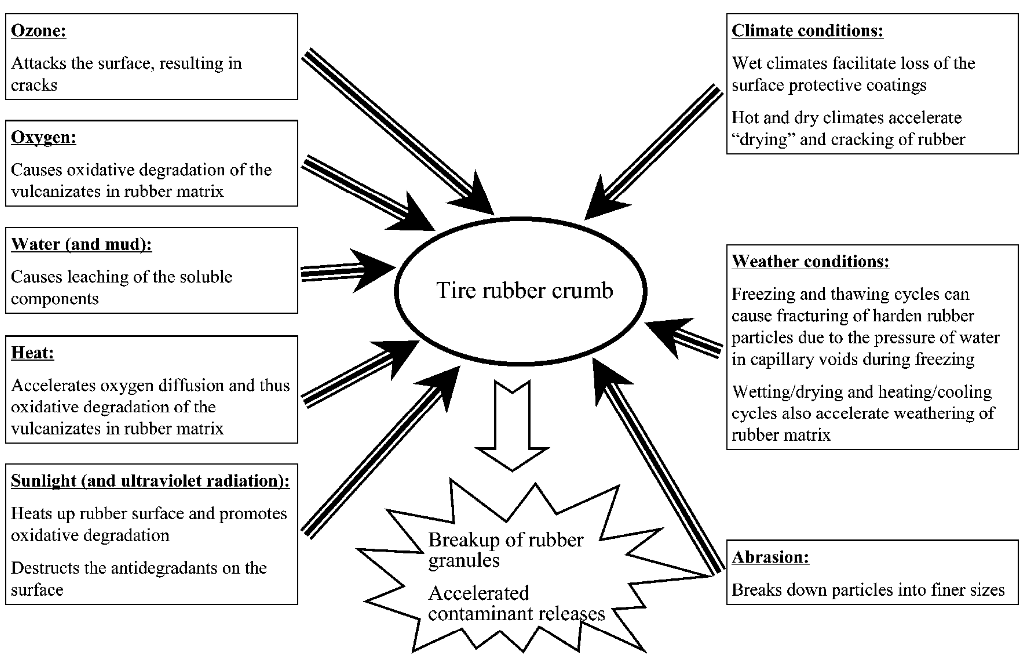

Figure 4. Influence of the major environmental factors on degradation of tire rubber crumb in artificial turf fields.

risk was found with the exposure to respirable particulates (PM_{10} and $PM_{2.5}$) at artificial turf fields in both outdoor and indoor settings, either.[52−55] Taken together, it appears that the health risk posed by tire rubber crumb used in both outdoor and indoor artificial turf fields to professional athletes and occasional users through inhalation is insignificant. Health risk evaluation results indicated that elevated health risk from inhalation exposure could occur only for workers installing artificial turf in small and poorly ventilated facilities with a long exposure history (>5 years).[52]

AREAS OF FURTHER RESEARCH

Although a number of studies have investigated the environmental release of potentially hazardous substances from artificial turf and its components, and exposure evaluations failed to demonstrate significant environmental and human health risks for typical field installations, several questions pertaining to the environmental impacts of artificial turf fields over their life cycle and their mitifation remain. Addressing these issues should help resolve uncertainties that still hamper the adoption of artificial turf at some sites.

Degradation of Tire Rubber Crumb under Field Conditions. Characterization of the environmental breakdown of tire rubber crumb is crucial for understanding the environmental impacts of artificial turf as this process is accompanied with release of the hazardous additives in the rubber matrix and the degradation products of rubber polymers. Although it is known that the cross-linked polymer matrix of tire rubber can degrade slowly under natural conditions,[74] factors that influence the aging of rubber crumb are poorly understood. As illustrated in Figure 4, exposure to oxygen, ozone, heat, sunlight, and liquids can all cause changes in the physical and chemical properties of tire rubber crumb, and correspondingly release of contaminants from the degraded rubber matrix. A range of additives and stabilizers are used in tire manufacturing to inhibit undesired/unwanted chemical reactions within the rubber components and to sustain their structural integrity and desired properties over an extended period of time. Oxygen in air permeates into tire rubber and causes oxidative degradation of the vulcanizates, while the much more reactive ozone almost exclusively attacks the surface causing cracks perpendicular to the direction of applied stress in the rubber.[75] Heat accelerates oxygen diffusion in rubber stock and thus the oxidative degradation.[76] Ultraviolet radiation and sunlight promote oxidative degradation and destruct the antidegradants on the rubber surface.[77] Water and mud cause leaching of the soluble components from the rubber surface. Climate and weather conditions also contribute to tire rubber degradation as a composite result of the actions of sunlight, temperature, and water. Overall, the interactions with all these environmental factors lead to aging of tire rubber (i.e., cracking, splitting, oxidizing, and overall deterioration).[75,78]

A range of antidegradants are used by tire manufacturers to inhibit the attacks of oxygen and ozone (and flex cracking as well): antioxidants to limit oxidative degradation of the vulcanizates, antiozonants to retard the occurrence or growth of cracks caused by ozone attack, and flex-crack inhibitors to limit the initiation or growth of cracks resulting from cyclic deformation (i.e., flexing) of tires.[11,16] In addition, waxes are used to provide ozone protection through formation of a chemically inert surface barrier. Because they can migrate freely in the rubber stock, waxes are squeezed out onto the surface as the tire rolls, which also helps bring fresh antiozonants to the outside surface. As the antidegradants are gradually lost or used up through the life of tires, aged tires have drastically reduced resistance to weathering and initiation and propagation of cracks compared to new ones.[79] Due to the loss of antidegradants, rubber crumb produced from scrap tires are subject to much more significant attacks from oxygen, ozone, and sunlight compared to virgin rubber. The specific surface areas of tire rubber crumb are much higher than those of scrap tires, and most of the surface area is newly created by grinding or other mechanical processes. As a result, the volatilization of organic contaminants into air, and the leaching of heavy metals and organic contaminants into the percolating water from tire rubber crumb are expected to be significantly increased compared to the bulky scrap tires. The small particle sizes of the tire rubber crumb also facilitate the aging process.[76−78] With their high surface-to-volume ratios, granules of tire rubber are subject to significant ozone attack, which occurs predominantly on the surface.[78] Oxidative degradation is also accelerated due to easier diffusion of oxygen into the rubber stock.[75] Under natural conditions, the protection effect of antidegradants left in the tire rubber crumb is also lost more easily from the granules of smaller sizes.[77] Furthermore, the diurnal cycle of heating and cooling, and the freezing and thawing, as well as the wetting and drying cycles associated with weather patterns, along with the abrasion of the granules during playing time all can enhance the degradation of tire rubber crumb. The breakup of tire rubber crumb further accelerates the degradation process, and concomitantly, the release of hazardous substances into the environment.

Tire rubber is extremely resistant to biodegradation because of its complex composition and the additives within its matrix.[74,80] Nonetheless, recent research showed that the activity of both aerobic and anaerobic microorganisms could devulcanize tire rubber polymers.[74,81] Thiobacillus ferrooxidans and Nocardia could cause microbial desulfurization of tire rubber granules,[81−84] and the degradation rate generally increased with decreasing particle size when the cell attachment efficiency was not a limiting factor.[84,85] Nonetheless, degradation of tire rubber granules caused by microbial attack is much less significant compared to the attack by atmospheric oxygen.[86] Given the highly variable physical conditions (e.g., moisture and temperature) in artificial turf fields, biodegradation of tire rubber crumb is not expected to be important compared to the abiotic degradation processes discussed above. Because of the complex actions of oxygen, ozone, sunlight, and water on rubber degradation, and the significantly variable conditions of artificial turf fields, it is necessary to study the degradation of tire rubber crumb under relevant conditions over their functional lifetimes.

Leaching Dynamics of Hazardous Substances. The impacts of artificial turf fields on the environment are expected to be localized but last throughout their functional lifetimes. To predict the long-term impacts of artificial turf fields and help designing appropriate environmental safeguards, it is necessary to understand the environmental release of toxic metals (e.g., Zn, Pb, and Cd) and organic contaminants (e.g., PAHs) on a fundamental basis. Heavy metals are nondegradable in comparison with organic contaminants, and hence persist in the recipient environment. Thus the accumulation of heavy metals released from artificial turf fields over long-term is of particular concern. The high contents of ZnO, and to a lesser degree, PbO and CdO, in the tire rubber crumb present a significant point source of these hazardous substances. A typical soccer pitch/field can contain a total of 1.2 tonnes of zinc (assuming the rubber crumb has an average ZnO content of 1.5%). It has been estimated that under natural conditions 10−40% of the Zn could be released from the fine tire debris (<100 μm) mixed in soils within one year.[87] If 10% of the ZnO in the tire rubber crumb of an artificial turf field were released over its functional lifetime (10−20 years), it would contaminate 24 000 m^3 of water to the secondary drinking water standard (5 mg/L), or 1 million m^3 of water to the USEPA's criteria maximum concentration (CMC, 120 μg/L) for the protection of freshwater aquatic life. Similarly, the potential leaching of Cd and Pb, which have much lower MCL and CMC values than Zn, also poses significant environmental concerns. Because of its negative environmental effect and high cost, the tire industry has attempted to reduce the use of ZnO in tires and substitute it with alternative vulcanization activators, but with limited success so far.[88,89] Therefore, the risk associated with Zn leaching from tire rubber crumb would remain for artificial turf fields in the foreseeable future.

Tire rubber also contains significant levels of PAHs, which originate from the highly aromatic (HA) oils added as extender oils and the carbon black added as a reinforcement filler during production (SI). Due to concerns on the harmful effects of PAHs on human health and the environment, tire manufacturers had begun to substitute HA oils with alternative extender oils since the 2000s.[90] Extender oils that contain more than 1 mg/kg of benzo[a]pyrene or 10 mg/kg of the EU-8 priority PAHs have been banned in tires manufactured in or imported into the European Union (EU) countries since 2010.[91] As a result, major tire manufacturers have been implementing the changes at their plants worldwide. Meanwhile, carbon black is still used as a reinforcement filler of choice in tire manufacturing, thus its contribution to PAHs in tire rubber is becoming relatively more important.[92] Overall, with the phase-out of HA oils in tire production, the contents of PAHs in tire rubber crumb are expected to decline significantly over this decade.

The risk on human health and the environment posed by heavy metals and organic contaminants occurring in artificial turf depends on the rates at which they are released and transported into the target organisms.[93] The hydrophobic PAHs in tire rubber crumb are not expected to desorb readily. It has been observed that the PAHs on commercial carbon black materials were not leached by artificial lung fluid,[94] and that the PAHs on carbon black incorporated in cured rubber formulations were scarcely available to various aqueous media.[95] Similarly, the rubber stock also has high affinity for HA oils and PAHs, and these organic contaminants are not expected to leach out easily. Therefore, characterizing the release of contaminants and their subsequent fate and transport under field conditions is critical to assess their actual risk. Many factors, such as the composition of the infill, and its particle size and age, the acidity of rainwater, and the ambient temperature are expected to affect the leaching rates of heavy metals and organic contaminants from tire rubber crumb, while the subsequent transport behaviors of the contaminants released are affected by their interactions with the underlying rock materials and pH of the drainage.[35,49] The long-term evolution of the contaminant release rates is difficult to predict: they can decrease over time due to the depletion of contaminants on the surface of the rubber granules, while the accelerated weathering of rubber granules exposed to sunlight, oxygen, ozone, and water/moisture can result in formation of cracks and possibly breakup of the rubber particles, which are expected to enhance their release.

Large-scale monitoring campaigns based on systematic random sampling of all artificial turf field sites can be cost- and resource-prohibitive. Thus carefully coordinated laboratory and field investigations are invaluable for characterizing the release of heavy metals and organic contaminants from artificial turf under relevant environmental conditions, as well as their transport behaviors along with the field drainage. It is particularly worthwhile to study the contaminant release under conditions representative of "worst case" scenarios (e.g., high temperatures and frequent rainfalls) to estimate the upper bound of impacts.

Management of Storm Drainage from Artificial Turf Fields. To mitigate the release of potentially hazardous substances from artificial turf fields into the aquatic environment, optimized treatment systems and management strategies are needed to remove the contaminants before the drainage is discharged into the receiving body. The gravel layers beneath the artificial turf serve as a reservoir for the rainwater fallen on the fields. The crushed rock used as a base material in the construction of artificial turf field (Figure 1b) has a neutralization effect on precipitation (e.g., acidic rainwater),[49] and can effectively retain Zn through sorption/coprecipitation.[35] Its presence in artificial turf fields help immobilize some of the heavy metals released from the tire rubber crumb, although the drainage of artificial turf fields still contained heavy metals at appreciable levels.[35,50,68] Given the relatively large areas of artificial turf fields, significant quantity of drainage can be collected for beneficial uses after proper treatment, such as field cleaning and irrigation of adjacent grass lawns.

Even though many of the contaminants that can be present in the drainage from artificial turf fields do not have relevant regulatory standards, it is prudent to treat the drainage to prevent potential synergistic impacts of the contaminants at low concentrations. The drainage is produced only intermittently and often has complex chemical composition with significant variations in the concentrations of the contaminants, thus conventional biological, physical, and chemical processes developed for removing organic contaminants and heavy metals from industrial and municipal wastewaters may not be effective. Besides the technical capability, the treatment process should also meet the criteria of being robust, low-cost, and easy to maintain. The hydrophobic organic contaminants (such as PAHs) can be adsorbed from aqueous solutions onto activated carbon, while heavy metals can be removed by mineral sorbents through sorption and coprecipitation. Therefore, mixed sorbents (e.g., activated carbon and mineral sorbents) packed in the configuration of a filtration bed or a permeable reactive barrier can be employed to remove the contaminants leached from tire rubber crumb. Such treatment system can be installed conveniently under the artificial turf fields to help mitigate the potential impact of field drainage on aquatic environment.

Disposal and Recycling of Artificial Turf Components. Typical artificial turf fields have functional lifetimes of 10−20 years. Rubber crumb and other components of artificial turf degrade upon exposure to sunlight, air, and water, and eventually must be disposed of. Landfilling is the default disposal option for scrap tires that are not recycled or reused. However, tires in any shape or form have been banned from landfills in the EU countries since 2006,[96] while landfilling of cut or shredded tires is currently allowed in only 36 states of the U.S.[4] Given the large mass of tire rubber crumb used in

dx.doi.org/10.1021/es4044193 | Environ. Sci. Technol. 2014, 48, 2114−2129

Table 3. Comparison of the Advantages and Limitations of the Major Types of Infill Material for Artificial Turf

type	advantages	limitations	cost	recyclability	field performance
silica sand	a natural mineral mined from gravel pits; durable; does not get very hot from absorbing the heat from the sun.	the playing surface is very hard and abrasive; weights more than the other infill products; compaction can occur; can generate dust.	least expensive	can be recycled or disposed of with little restriction.	widely used in the second generation artificial turf
tire rubber crumb	provides excellent stability, uniformity, and resiliency; proven durability and performance; made from postconsumer recycled materials; does not harden or change composition, allowing the surface to stay consistent over time.	small rubber particles easily stick onto clothes and skin; retains heat from the sun and can get very hot; may release volatile and semivolatile organic contaminants into the air; may leach heavy metals and organic contaminants into water.	more expensive than silica sand	can be recycled or disposed of in landfills	has been field tested and proven for performance over many years
silica sand and tire rubber crumb mixture	provides a firmer playing surface than rubber only infill; mixed infill helps ensure optimal field safety and playability.	segregation of the rubber and sand particles can occur and the mixed infill needs to be loosened periodically.	costs less than rubber only infill	tire rubber crumb can be separated from sand, and subsequently recycled or disposed of in landfills	has been field tested and proven for performance over many years
thermoplastic elastomers	made from virgin materials that do not contain hazardous additives; less heat absorption when exposed to the sun compared to rubber infill.	subject to wide manufacturing variations; may harden over time; some products do not provide enough flexibility and crush resistance; some products do not contain ultraviolet stabilizers and undergo degradation relatively.	very expensive	recyclable	the durability and performance remain to be proven
EPDM rubber	made from virgin material that does not contain hazardous additives; durable and more environmentally friendly than tire rubber; available in a variety of colors; less heat absorption when exposed to the sun compared to rubber infill.	chemicals used in the rubber manufacturing can leach into the contacting water	very expensive	recyclable	has been used in european countries, yet the durability and performance remain to be proven
organic infill	derived from natural plant fibers and cork; nontoxic and truly environmentally friendly; less heat absorption when exposed to the sun compared to rubber infill; resists wear and ultraviolet rays.	requires antimicrobial treatment to prevent degradation; may break down; may be infected by insects; compaction can occur over time.	relatively inexpensive	can be recycled into other products	new to the market, and has no track record for durability
rubber coated sand	does not contain hazardous additives; eliminates the compaction and dust issues of sand; less heat absorption when exposed to the sun compared to rubber infill.	a softer filler material need to be added to the acrylic material; coating may break down over time.	more expensive than sand infill	can be recycled	new to the market, and has no track record for durability

dx.doi.org/10.1021/es4044193 | Environ. Sci. Technol. 2014, 48, 2114−2129

artificial turf fields, effective treatment or recycling schemes must be developed to minimize the environmental impacts upon disposal. A potential solution is to use the spent tire rubber crumb as tire-derived fuel to supplement traditional fuels (SI), although attention should be paid to control the potential emissions of heavy metals contained in the rubber and toxic organic contaminants, such as PAHs, and dioxins and furans (due to the presence of chlorine in tires) during burning.[97] The plastic fibers and carpet backing of artificial turf used to be landfilled at the end of the field's functional lifetime. A few companies have started to offer the alternative of full field recycling for artificial turf since 2010. After thorough separation of the infill materials, the plastics are shredded, repalletized, and converted into useable materials for new artificial turf applications or other extruded plastic products.

Development of Alternative Infill Materials. The human health and environmental risk of artificial turf can be eliminated or reduced by substituting the tire rubber crumb with alternative infill materials containing less hazardous substances. Several alternative infill materials have been developed by artificial turf and rubber manufacturers.[6,48] Table 3 summarizes the advantages and limitations of the six major types of infill materials available on the market. Even though the alternative infill materials contain much less hazardous substances than tire rubber crumb, they are often considerably more expensive. Besides the criterion of containing minimum hazardous substances, the safety, durability, and cost of the infill materials are also important considerations. Sand and tire rubber crumb have been field tested and proven for several decades, while the performance and environmental friendliness of the newly emerged infill materials, including thermoplastic elastomers, ethylene propylene diene monomer (EPDM) rubber, organic infill, and rubber coated sand remain to be field proven.[6] Furthermore, some of the alternative infill materials also release organic contaminants and have environmental impacts similar to those of tire rubber crumb.[7,52,70,98] It may take years to develop environmentally friendly alternative infill materials that can match the durability and performance of tire rubber crumb. It should be noted that raw materials and energy are required for the production of most of these alternatives, in addition to the lost benefits of reusing scrap tires. Thus the life cycle environmental impacts should also be considered when developing substitutes for tire rubber crumb in artificial turf.

PERSPECTIVE ON THE TURF WAR

Recycling and reuse of tire rubber in artificial turf contribute to sustainable development by reducing the dependence on new materials, waste generation, and energy consumption. The limited number of studies conducted to date appear to indicate that the concentrations of hazardous substances in the drainage from artificial turf fields and in the air above them are relatively low and of no significant concern. Nonetheless, the release of organic contaminants and heavy metals into the air, water, and soil in the surrounding environment occurs continuously, and their cumulative masses can be significant over the fields' functional lifetimes. There remains a significant knowledge gap that must be urgently addressed with the fast expansion of the artificial turf market. Given the wide range of designs, ages, and conditions of artificial turf fields, it is likely that the contaminant release and the environmental impacts are variable from site to site. It is also important to assess more systematically the risk posed by the tire rubber crumb on the environment and human health. The contents of some hazardous substances, such PAHs, in tire rubber are expected to decrease over time as the industry becomes more environmentally conscious, which is going to reduce the associated risk in artificial turf. Meanwhile, the development of alternative infill materials for replacing the tire rubber crumb, which may significantly increase the cost of artificial turf, will help eliminate some of the major environmental concerns. Overall, manufacturers are expected to produce more environmentally friendly artificial turf as the general public become increasingly concerned with its negative environmental impacts.

It is worth pointing out that the turf grass industry has also been making significant progress in developing new types of grass to meet the water challenges and the increasing environmental concerns associated with fertilizer and pesticide applications. Improved turf grasses can be extremely drought-tolerant, tough, and fast-growing, while having lower requirement for fertilizers and maintenance. Organic fertilizers that can eliminate most of the environmental issues associated with chemical fertilizers are also available. These advances have greatly reduced the necessity of artificial turf in warm climates. On the other hand, artificial turf appears to be the most viable playing surface currently available in indoor sports facilities, in the cold climates where the prime growing season of turf grass is rather short, and in the dry climates and other zones with scarce water resources.

Natural grass and artificial turf each have their advantages and limitations (Table 1). Despite the existence of methods for estimating their life cycle costs and environmental impacts, a generally applicable methodology to compare objectively and quantitatively the benefits and impacts of natural grass and artificial turf is difficult because some of these attributes are unrelated (belong to different categories) and site specific, and depend on how users value them.

ASSOCIATED CONTENT

*** Supporting Information**

Additional information on disposal of scrap tires, composition of tire rubber and production of tire rubber crumb, ZnO and PAHs in tire rubber, assumptions in the LCA studies, conditions and major findings of selected TCLP studies on ground tire rubber and tire chips, potential organic contaminants that can be leached from tire rubber, composition of passenger and truck tires, composition of tire rubber ash, and scrap tire management in the U.S. (2005−2009) is available. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

*Phone: (+86) 20 8529-0175; fax: (+86) 20 8529-0706; e-mail: hefac@umich.edu.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We gratefully acknowledge the anonymous reviewers for their valuable comments and suggestions. This work was supported in parts by the Natural Science Foundation of China (Grant Nos. 41121063, 41202251, and 41322024), Santa Clara Valley Water District, the SRF for ROCS, SEM, the Chinese Academy of Sciences (Y234081A07 and "Interdisciplinary Collaboration

Team" programs), the Special Support Program of the Organization Department of CCCPC, and the National Science Foundation Engineering Research Center for Re-Inventing the Nation's Urban Water Infrastructure (ReNUWIt).

REFERENCES

(1) Fordyce, B. 2011. Turf war: artificial vs. natural. http://landscapeonline.com/research/article/14635.

(2) Farris, R. J.; Williams, D. E.; Morin, J. E.; Tripathy, A. R. Powder Processing Techniques to Recycle Rubber Tires into New Parts from 100% Reclaimed Rubber Powder/Crumb, Technical Report #40; Chelsea Center for Recycling and Economic Development: Chelsea, MA, 2001.

(3) FieldTurf. FieldTurf Corporate Brochure 2012; Calhoun, GA, 2012.

(4) Rubber Manufacturers Association (RMA). U.S. Scrap Tire Management Summary 2005−2009; ; Washington, DC, 2011.

(5) Doyle, R. Synthetic success, Sports Field Management Magzine, 2012. http://www.sportsfieldmanagementmagazine.com/print-8030.aspx.

(6) Lavorgna, J.; Song, J.; Beattie, W.; Riley, M.; Beil, C.; Levchenko, K.; Shofar, S. A Review of Benefits and Issues Associated with Natural Grass and Artificial Turf Rectangular Stadium Fields • Final Report; Montgomery County Council: Rockville, MD, 2011.

(7) Kruger, O.; Kalbe, U.; Berger, W.; Nordhauβ, K.; Christoph, G.; Walzel, H.-P. Comparison of batch and column tests for the elution of artificial turf system components. Environ. Sci. Technol. 2012, 46 (24), 13085−13092.

(8) Li, X.; Berger, W.; Musante, C.; Mattina, M. I. Characterization of substances released from crumb rubber material used on artificial turf fields. Chemosphere 2010, 80 (3), 279−285.

(9) Menichini, E.; Abate, V.; Attias, L.; De Luca, S.; Di Domenico, A.; Fochi, I.; Forte, G.; Iacovella, N.; Iamiceli, A. L.; Izzo, P.; Merli, F.; Bocca, B. Artificial-turf playing fields: Contents of metals, PAHs, PCBs, PCDDs and PCDFs, inhalation exposure to PAHs and related preliminary risk assessment. Sci. Total Environ. 2011, 409 (23), 4950−4957.

(10) Van Ulirsch, G.; Gleason, K.; Gerstenberger, S.; Moffett, D. B.; Pulliam, G.; Ahmed, T.; Fagliano, J. Evaluating and regulating lead in synthetic turf. Environ. Health Perspect. 2010, 118 (10), 1345−1349.

(11) Thornley, E. R. Role of antiozonants in modern tire compounding. Rubber Chem. Technol. 1964, 37 (4), 973−989.

(12) Hartwell, S. I.; Jordahl, D. M.; Dawson, C. E. O. The effect of salinity on tire leachate toxicity. Water, Air, Soil Pollut. 2000, 121 (1−4), 119−131.

(13) Peterson, J. C.; Clark, D. F.; Sleevi, P. S. Tire fire oil: Monitoring a new environmental pollutant. Anal. Chem. 1986, 58 (1), 70A−72A.

(14) Day, K. E.; Holtze, K. E.; Metcalfe-Smith, J. L.; Bishop, C. T.; Dutka, B. J. Toxicity of leachate from automobile tires to aquatic biota. Chemosphere 1993, 27 (4), 665−675.

(15) Evans, J. J. Rubber tire leachates in the aquatic environment. Rev. Environ. Contam. Toxicol. 1997, 151, 67−115.

(16) Ambelang, J. C.; Kline, R. H.; Lorenz, O. M.; Parks, C. R.; Wadelin, C.; Shelton, J. R. Antioxidants and antiozonants for general purpose elastomers. Rubber Chem. Technol. 1963, 36 (5), 1497−1541.

(17) Rappaport, S. M.; Fraser, D. A. Gas chromatographic-mass spectrometric identification of volatiles released from a rubber stock during simulated vulcanization. Anal. Chem. 1976, 48 (3), 476−481.

(18) Conesa, J. A.; Fullana, A.; Font, R. Tire Pyrolysis: Evolution of volatile and semivolatile compounds. Energy Fuels 2000, 14 (2), 409−418.

(19) Chien, Y.-C.; Ton, S.; Lee, M.-H.; Chia, T.; Shu, H.-Y.; Wu, Y.-S. Assessment of occupational health hazards in scrap-tire shredding facilities. Sci. Total Environ. 2003, 309 (1−3), 35−46.

(20) Al-Tabbaa, A.; Aravinthan, T. Natural clay-shredded tire mixtures as landfill barrier materials. Waste Manag. 1998, 18 (1), 9−16.

(21) Downs, L. A.; Humphrey, D. N.; Katz, L. E.; Rock, C. A. Water Quality Effects of Using Tire Chips below the Groundwater Table. Technical Report 94-l; Department of Civil Environmental Engineering, University of Maine, Orono, 1996.

(22) Zelibor, J. L. The RMA TCLP Assessment Project: Leachate from Tire Samples; Scrap Tire Management Council, 1991.

(23) Khan, A. A.; Karanfil, T.; Selbes, M. The Feasibility of Tire Chips As a Substitute for Stone Aggregate in Septic Tank Leach Fields, Final Report Part-II; Clemson University, 2011.

(24) Spagnoli, J.; Weber, A.; Zicari, L. The Use of Tire Chips in Septic System Leachfields; Center for Integrated Waste Management, State University of New York at Buffalo: Buffalo, NY, 2001.

(25) Nelson, S. M.; Mueller, G.; Hemphill, D. C. Identification of tire leachate toxicants and a risk assessment of water quality effects using tire reefs in canals. Bull. Environ. Contam. Toxicol. 1994, 52 (4), 574−581.

(26) Stephensen, E.; Adolfsson-erici, M.; Celander, M.; Hulander, M.; Parkkonen, J.; Hegelund, T.; Sturve, J.; Hasselberg, L.; Bengtsson, M.; Foerlin, L. Biomarker responses and chemical analyses in fish indicate leakage of polycyclic aromatic hydrocarbons and other compounds from car tire rubber. Environ. Toxicol. Chem. 2003, 22 (12), 2926−2931.

(27) Humphrey, D. N.; Katz, L. E. Water-quality effects of tire shreds placed above the water table. Five-year field study. Transport. Res. Rec. 2000, 1714, 18−24.

(28) Lerner, A.; Naugle, A.; LaForest, J.; Loomis, W. A Study of Waste Tire Leachability in Potential Disposal and Usage Environments, Amended Vol. 1: Final Teport; Department of Environmental Engineering Sciences, University of Florida, 1993.

(29) O'Shaughnessy, V.; Garga, V. K. Tire-reinforced earthfill. Part 3: Environmental assessment. Can. Geotech. J. 2000, 37 (1), 117−131.

(30) Sengupta, S.; Miller, H. Investigation of tire shreds for use in residential subsurface leaching field systems: A field scale study. In Proceedings of the 33rd Mid-Atlantic Industrial and Hazardous Waste Conference, 2001; pp 104−113.

(31) Liu, H. S.; Mead, J. L.; Stacer, R. G. Environmental effects of recycled rubber in light-fill applications. Rubber Chem. Technol. 2000, 73 (3), 551−564.

(32) Sheehan, P. J.; Warmerdam, J. M.; Ogle, S.; Humphrey, D. N.; Patenaude, S. M. Evaluating the risk to aquatic ecosystems posed by leachate from tire shred fill in roads using toxicity tests, toxicity identification evaluations, and groundwater modeling. Environ. Toxicol. Chem. 2006, 25 (2), 400−411.

(33) Rhodes, E. P.; Ren, Z.; Mays, D. C. Zinc leaching from tire crumb rubber. Environ. Sci. Technol. 2012, 46 (23), 12856−12863.

(34) Bocca, B.; Forte, G.; Petrucci, F.; Costantini, S.; Izzo, P. Metals contained and leached from rubber granulates used in synthetic turf areas. Sci. Total Environ. 2009, 407 (7), 2183−2190.

(35) Cheng, H.; Reinhard, M. Field, Pilot, And Laboratory Studies for the Assessment of Water Quality Impacts of Artificial Turf; Santa Clara Valley Water District: San Jose, CA, 2010.

(36) Humphrey, D. N.; Katz, L. E.; Blumenthal, M. Water quality effects of tire chip fills placed above the groundwater table. ASTM Spec. Tech. Publ. 1997, 1275, 299−313.

(37) Edil, T. B.; Bosscher, P. J. Development of Engineering Criteria for Shredded Waste Tires in Highway Applications. Final Report to Wisconsin; Department of Transportation and Natural Resources, Madison, WI, 1992.

(38) Wik, A.; Dave, G. Environmental labeling of car tires • Toxicity to Daphnia magna can be used as a screening method. Chemosphere 2005, 58 (5), 645−651.

(39) Wik, A.; Dave, G. Acute toxicity of leachates of tire wear material to Daphnia magna • Variability and toxic component. Chemosphere 2006, 64 (10), 1777−1784.

(40) Gualtieri, M.; Andrioletti, M.; Mantecca, P.; Vismara, C.; Camatini, M. Impact of tire debris on in vitro and in vivo systems. Part. Fibre Toxicol. 2005, 2 (1), 1−14.

(41) Gualtieri, M.; Rigamonti, L.; Galeotti, V.; Camatini, M. Toxicity of tire debris extracts on human lung cell line A549. Toxicol. In Vitro 2005, 19 (7), 1001−1008.
(42) Sheehan, P. J.; Warmerdam, J. M.; Ogle, S.; Humphrey, D. N.; Patenaude, S. M. Evaluating the risk to aquatic ecosystems posed by leachate from tire shred fill in roads using toxicity tests, toxicity identification evaluations, and groundwater modeling. Environ. Toxicol. Chem. 2006, 25 (2), 400−411.
(43) Birkholz, D. A.; Belton, K. L.; Guidotti, T. L. Toxicological evaluation for the hazard assessment of tire crumb for use in public playgrounds. J. Air Waste Manag. Assoc. 2003, 53 (7), 903−907.
(44) New Jersey Department of Health and Senior Services (NJDHSS). Lead and Artificial Turf Fact Sheet; Trenton, NJ, 2008.
(45) Synturf.org, Lead. http://www.synturf.org/lead.html.
(46) U.S. Environmental Protection Agency (USEPA) A Scoping-Level Field Monitoring Study of Synthetic Turf Fields and Playgrounds, EPA/600/R-09/135; Washing, DC, 2009.
(47) Lim, L.; Walker, R. An Assessment of Chemical Leaching: Releases to Air and Temperature at Crumb-Rubber Infilled Synthetic Turf Fields; New York State Department of Environmental Conservation, New York State Department of Health, 2009.
(48) Denly, E.; Rutkowski, K.; Vetrano, K. M. A Review of the Potential Health and Safety Risks from Synthetic Turf Fields Containing Crumb Rubber Infill; New York City Department of Health and Mental Hygiene: New York, NY, 2008.
(49) Bristol, S. G.; McDermott, V. C. Evaluation of Benzothiazole, 4-(Tert-Octyl) Phenol and Volatile Nitrosamines in Air at Synthetic Turf Athletic Fields; Milone & MacBroom, Inc.: Cheshire, CT, 2008.
(50) Bristol, S. G.; McDermott, V. C. Evaluation of Stormwater Drainage Quality from Synthetic Turf Athletic Fields; Milone & MacBroom, Inc: Cheshire, CT, 2008.
(51) Simon, R. Review of the Impacts of Crumb Rubber in Artificial Turf Applications; University of California, Berkeley, CA, 2010.
(52) Moretto, R. Environmental and Health Assessment of the Use of Elastomer Granulates (Virgin and from Used Tyres) As Filling in Third-Generation Artificial Turf; ADEME/ALIAPUR/Fieldturf Tarkett, 2007.
(53) Dye, C.; Bjerke, A.; Schmidbauer, N.; Mano, S. Measurement of Air Pollution in Indoor Artificial Turf Halls, Report NILU OR 03/2006; Norwegian Institute for Air Research: Kjeller, Norway, 2006.
(54) Norwegian Institute of Public Health and the Radium Hospital. Synthetic Turf Pitches・An Assessment of Health Risks for Football Players; Oslo, Norway, 2006.
(55) Rubber Manufacturers Association (RMA). Review of the Human Health & Ecological Safety of Exposure to Recycled Tire Rubber Found at Playgrounds and Synthetic Turf Fields; Washington, DC, 2008.
(56) Park, J. K.; Edil, T. B.; Kim, J. Y.; Huh, M.; Lee, S. H.; Lee, J. J. Suitability of shredded tyres as a substitute for a landfill leachate collection medium. Waste Manag. Res. 2003, 21 (3), 278−289.
(57) Gunasekara, A. S.; Donovan, J. A.; Xing, B. Ground discarded tires remove naphthalene, toluene, and mercury from water. Chemosphere 2000, 41 (8), 1155−1160.
(58) Conner, J. R.; Smith, F. G. Immobilization of low level hazardous organics using recycled materials. ASTM Spec. Tech. Publ. 1996, 1240, 52−72.
(59) Alamo, L.; Calisir, F.; Roman, F.; Perales-Perez, O. Use of Recycled Crumb Rubber to Remove Heavy Metal Ions from Aqueous Solutions, Abstracts of Papers, 229th ACS National Meeting, 2005; IEC-045.
(60) Eisler, R. Zinc Hazards to Fish, Wildlife and Invertebrates: A Synoptic Review, Contaminant Hazard Reviews, Report 26; US Department on the Interior Fish and Wildlife Service, Patuxent Wildlife Research Center: Laurel, MD, 1993; pp 1−126.
(61) Meil, J.; Bushi, L. Estimating the Required Global Warming Offsets to Achieve a Carbon Neutral Synthetic Field Turf System Installation; Athena Institute: Ontario, Canada, 2007.
(62) Uhlman, B.; Diwan, M.; Dobson, M.; Sferrazza, R.; Songer, P. Synthetic Turf, Eco-Efficiency Analysis Final Report; BASF Corporation: Florham Park, NJ, 2010.
(63) Brentner, L. B.; Eckelman, M. J.; Zimmerman, J. B. Combinatorial life cycle assessment to inform process design of industrial production of algal biodiesel. Environ. Sci. Technol. 2011, 45 (16), 7060−7067.
(64) Lave, L. B. Using input-output analysis to estimate economy-wide discharges. Environ. Sci. Technol. 1995, 29 (9), 420A−426A.
(65) Vidair, C.; Haas, R.; Schlag, R. Evaluation of Health Effects of Recycled Waste Tires in Playground and Track Products; California Integrated Waste Management Board: Sacramento, CA, 2007.
(66) Brown, D. R. Artificial Turf: Exposures to Ground-up Rubber Tires Athletic Fields/Playgrounds/Gardening Mulch; Environment & Human Health, Inc.: North Haven, CT, 2007.
(67) Johns, D. M. Initial Evaluation of Potential Human Health Risks Associated with Playing on Synthetic Turf Fields on Bainbridge Island; Windward Environmental LLC: Seattle, WA, 2008.
(68) Hofstra, U. Environmental and Health Risks of Rubber Infill. Rubber Crumb from Car Tyres As Infill on Synthetic Turf; INTRON: The Netherlands, 2007.
(69) Ledoux, T. Preliminary Assessment of the Toxicity from Exposure to Crumb Rubber: Its Use in Playgrounds and Artificial Turf Playing Fields; New Jersey Department of Environmental Protection: Trenton, NJ, 2007.
(70) Plesser, T. S.; Lund, O. J. Potential Health and Environmental Effects Linked to Artificial Turf System・Final Report. Project No/Archive no O-10820; Norwegian Building Research Institute: Oslo, Norway, 2004.
(71) U.S. Consumer Product Safety Commission (CPSC), CPSC Staff Analysis and Assessment of Synthetic Turf Grass Blades; Bethesda, MD, 2008.
(72) Van Rooij, J. G.; Jongeneelen, F. J. Hydroxypyrene in urine of football players after playing on artificial sports field with tire crumb infill. Int. Arch. Occup. Environ. Health 2010, 83 (1), 105−110.
(73) Instituto de Biomechanica de Valencia (IBV). Study of Incidence of Recycled Rubber from Tyres in Environment and Human Health; International Association for Sports Surface Science Technical Meeting: Dresden, 2006.
(74) Stevenson, K.; Stallwood, B.; Hart, A. G. Tire rubber recycling and bioremediation: A review. Biorem. J. 2008, 12 (1), 1−11.
(75) Bateman, L.; Allen, P. W.; Re, N. R. P. The Chemistry and Physics of Rubber-Like Substances; Maclaren London, 1963.
(76) LaCount, B. J.; Castro, J. M.; Ignatz-Hoover, F. Development of a service-simulating, accelerated aging test method for exterior tire rubber compounds II. Design and development of an accelerated outdoor aging simulator. Polym. Degrad. Stab. 2002, 75 (2), 213−227.
(77) Huang, D.; LaCount, B. J.; Castro, J. M.; Ignatz-Hoover, F. Development of a service-simulating, accelerated aging test method for exterior tire rubber compounds I. Cyclic aging. Polym. Degrad. Stab. 2001, 74 (2), 353−362.
(78) Natural Rubber Science and Technology; Roberts, A. D., Ed.; Oxford University Press: New York, 1988.
(79) Baldwin, J. M.; Bauer, D. R. Rubber oxidation and tire aging・A review. Rubber Chem. Technol,. 2008, 81 (2), 338−358.
(80) Zabaniotou, A. A.; Stavropoulos, G. Pyrolysis of used automobile tires and residual char utilization. J. Anal. Appl. Pyrolysis 2003, 70 (2), 711−722.
(81) Chritiansson, M.; Stenberg, B.; Wallenberg, L.; Holst, O. Reduction of surface sulphur upon microbial devulcanization of rubber materials. Biotechnol. Lett. 1998, 20 (7), 637−642.
(82) Li, Y.; Zhao, S.; Wang, Y. Microbial desulfurization of ground tire rubber by Thiobacillus ferrooxidans. Polym. Degrad. Stab. 2011, 96 (9), 1662−1668.
(83) Tsuchii, A.; Tokiwa, Y. Colonization and disintegration of tire rubber by a colonial mutant of Nocardia. J. Biosci. Bioeng. 1999, 87 (4), 542−544.
(84) Tsuchii, A.; Tokiwa, Y. Microbial degradation of tyre rubber particles. Biotechnol. Lett. 2001, 23 (12), 963−969.
(85) Tsuchii, A.; Takeda, K.; Suzuki, T.; Tokiwa, Y. Colonization and degradation of rubber pieces by Nocardia sp. Biodegradation 1996, 7 (1), 41−48.

(86) Cadle, S. H.; Williams, R. L. Environmental degradation of tire-wear particles. Rubber Chem. Technol. 1980, 53 (4), 903−914.
(87) Smolders, E.; Degryse, F. Fate and effect of zinc from tire debris in soil. Environ. Sci. Technol. 2002, 36 (17), 3706−3710.
(88) Guzmán, M.; Reyes, G.; Agulló, N.; Borrós, S. Synthesis of Zn/Mg oxide nanoparticles and its influence on sulfur vulcanization. J. Appl. Polym. Sci. 2011, 119 (4), 2048−2057.
(89) Guzmán, M.; Vega, B.; Agulló, N.; Borrós, S. Zinc oxide versus magnesium oxide revisited. Part 2. Rubber Chem. Technol. 2012, 85 (1), 56−67.
(90) Ahlbom, J.; Duus, U. HA Oils in Automotive Tyres • prospects of a National Ban, KEMI Report No. 5/03; Swedish Chemicals Inspectorate: Sundbyberg, Sweden, 2003.
(91) European Commission. Regulation no 552/2009 of 22 June 2009 amending Regulation (EC) No 1907/2006 of the European Parliament and of the Council on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) as regards Annex XVII, 2009.
(92) Sadiktsis, I.; Bergvall, C.; Johansson, C.; Westerholm, R. Automobile tires • A potential source of highly carcinogenic dibenzopyrenes to the environment. Environ. Sci. Technol. 2012, 46 (6), 3326−3334.
(93) Swedish Chemicals Inspectorate. Artificial Turf from a Chemical Perspective • A Status Report, KEMI Report No. 3/06; Swedish Chemicals Inspecorate: Sundbyberg, Sweden, 2006.
(94) Borm, P. J. A.; Cakmak, G.; Jermann, E.; Weishaupt, C.; Kempers, P.; van Schooten, F. J.; Oberdorster, G.; Schins, R. P. F. Formation of PAH-DNA adducts after in vivo and vitro exposure of rats and lung cells to different commercial carbon blacks. Toxicol. Appl. Pharmacol. 2005, 205 (2), 157−167.
(95) Hamm, S.; Frey, T.; Weinand, R.; Moninot, G.; Petiniot, N. Investigations on the extraction and migration behavior of polycyclic aromatic hydrocarbons (PAHs) from cured rubber formulations containing carbon black as reinforcing agent. Rubber Chem. Technol. 2009, 82 (2), 214−228.
(96) Council of the European Union, Council Directive of 26 April 1999 on the Landfill of Waste (1999/31/EC). Off J. Eur. Union, 1999, L 182 16.7.1999, 1−19.
(97) Cheng, H.; Hu, Y. Curbing dioxin emissions from municipal solid waste incineration in China: Re-thinking about management policies and practices. Environ. Pollut. 2010, 158 (9), 2809−2814.
(98) Nilsson, N. H.; Malmgren-Hansen, B.; Thomsen, U. S. Mapping, Emissions and Environmental and Health Assessment of Chemical Substances in Artificial Turf; Danish Environmental Protection Agency: Copenhagen, Denmark, 2008.
(99) Meyers, M. C.; Barnhill, B. S. Incidence, causes, and severity of high school football injuries on field turf versus natural grass a 5-year prospective study. Am. J. Sports Med. 2004, 32 (7), 1626−1638.
(100) Orchard, J. W.; Powell, J. W. Risk of knee and ankle sprains under various weather conditions in American football. Med. Sci. Sports Exercise 2003, 35 (7), 1118−1123.
(101) Fuller, C. W.; Dick, R. W.; Corlette, J.; Schmalz, R. Comparison of the incidence, nature and cause of injuries sustained on grass and new generation artificial turf by male and female football players. Part 1: Match injuries. Br. J. Sports Med. 2007, 41 (S1), i20−i26.
(102) Fuller, C. W.; Dick, R. W.; Corlette, J.; Schmalz, R. Comparison of the incidence, nature and cause of injuries sustained on grass and new generation artificial turf by male and female football players. Part 2: Training injuries. Br. J. Sports Med. 2007, 41 (S1), i27−i32.
(103) Meyers, M. C. Incidence, mechanisms, and severity of game-related college football injuries on fieldturf versus natural grass a 3-year prospective study. Am. J. Sports Med. 2010, 38 (4), 687−697.
(104) Beard, J. B.; Green, R. L. The role of turfgrasses in environmental protection and their benefits to humans. J. Environ. Qual. 1994, 23 (3), 452−460.
(105) Townsend-Small, A.; Czimczik, C. I. Carbon sequestration and greenhouse gas emissions in urban turf. Geophys. Res. Lett. 2010, 37 (2), L02707.
(106) Kirstine, W.; Galbally, I.; Ye, Y.; Hooper, M. Emissions of volatile organic compounds (primarily oxygenated species) from pasture. J. Geophys. Res. 1998, 103 (D9), 10605−10619.
(107) Kirstine, W. V.; Galbally, I. E. A simple model for estimating emissions of volatile organic compounds from grass and cut grass in urban airsheds and its application to two Australian cities. J. Air Waste Manag. Assoc. 2004, 54 (10), 1299−1311.

Supporting Information

for

Environmental and Health Impacts of Artificial Turf: A Review

Hefa Cheng[1], Yuanan Hu[1], Martin Reinhard[2]*

1 State Key Laboratory of Organic Geochemistry

Guangzhou Institute of Geochemistry, Chinese Academy of Sciences

Guangzhou 510640, China

2 Department of Civil and Environmental Engineering

Stanford University

Stanford, CA 94305, USA

Environmental Science and Technology

Date: Dec. 15, 2013

Number of Pages: 16

Number of Tables: 4

Number of Figure: 1

1. Disposal of Scrap Tires

Tires are generally considered relatively benign in the environment unless subjected to high temperatures. Nonetheless, disposal of scrap tires, which are composed primarily of chemically cross-linked rubber, is a major problem for waste management because they are highly durable and are generated in large quantities each year.[1] Most landfills do not accept scrap tires because they tend to float to the surface after being buried, which can break the landfill caps.[2] Abandoned or stockpiled scrap tires not only occupy large areas of land, but also serve as potential breeding grounds for rodents and mosquitoes.[2] As they can trap heat, stockpiled scrap tires also present a fire hazard.[2] Tire fires release soot and hundreds of toxic contaminants, and are very difficult to put out.[3,4] Obviously finding a market for these slow-to-decompose materials is desirable, and many innovative uses have been developed. A total of 291.8 million scrap tires (with an average weight of 33.4 lbs) were generated in the U.S. in 2009, with 83.1% of them being managed or utilized.[5] Figure S1 shows the trend of scrap tire management in the U.S. between 2005 and 2009. The high cost of energy and the growing demands for tire rubber crumb in sports field and playground surfacing have led to increased utilization of scrap tires in recent years. Most of the scrap tires were recycled or found beneficial uses, primarily in the forms of tire derived fuel, ground rubber, and civil engineering applications, while only a small fraction of them were land disposed.[5] Of the more than 0.71 million tonnes of ground rubber consumed in the U.S. in 2009, most was used in the molded/extruded products (31.8%), sports surfacing (25.4%), playgrounds/mulch/animal bedding (20.3%), and rubber-modified asphalt (11.1%).[5] It should be noted that a truly environmentally friendly method for scrap tire disposal remains to be found, despite the availability of plenty of scrap tire recycling and reuse options.

2. Composition of Tire Rubber and Production of Tire Rubber Crumb

Automotive tires are made of layers of steel and fabric reinforcing materials surrounded by a protective casing of rubber mixed with various additives (Table S3). Besides the dominant steel-belted radial ply type, tires can also be polyester-, Nylon-, Rayon-, fiberglass-, and Kevlar-belted, while most tires today use both steel and polymer belts. Inorganic materials are used for various purposes in tire production. ZnO, Fe_2O_3, Al_2O_3, and TiO_2 are the major metal oxides in the ash of both passenger and truck tires, while low levels of PbO, Cr_2O_3, BaO, and CdO are also found (Table S4). In particular, ZnO is used as a vulcanizing agent in tire production in large quantities: the representative weighted average contents are 2% (range: 0.4-2.9%) and 2.1% (range: 1.2-4.3%) in the treads of passenger and truck tires, respectively.[6] Silica and carbon black are common reinforcement fillers and are often present at substantial levels in tire rubber (Table S3).

Tire rubber crumb is composed of wire-free fine rubber particles made by size reduction of scrap tires. Two major categories of techniques are used to obtain rubber crumb with a wide range of particle sizes (down to 600 microns or less).[7] The most commonly used process is mechanical grinding, which breaks down the rubber into small particles with cracker mill or granulator. The shape and surface texture of the rubber particles produced this way are relatively round and smooth. Cryogenic method, which consists of freezing the shredded rubber at an extremely low temperature (far below the glass transition temperature of the compound, usually with liquid nitrogen) and then shattering it into small particles, produces rubber with fine mesh sizes.[7] Steel wires and fabric components are subsequently removed by magnetic separator, air classifier, or other separation equipment. As a result, tire rubber crumb is expected to retain most of the chemical additives contained in the rubber stock.

3. ZnO and PAHs in Tire Rubber

As an excellent activator for sulfur vulcanization, ZnO is used widely in the rubber industry and is found in essentially all rubber products. ZnO in tire rubber also enhances tire performance by improving its ability to absorb frictional heat. ZnO is typically used in rubber formulations at the levels of 2-10 per hundred rubber (i.e., parts of the non-rubber ingredients per 100 parts of rubber hydrocarbons in the rubber recipe).[8] The global consumption of ZnO exceeds 1.2 million tonnes annually, with the rubber industry accounting for over half of the total demand.[9] According to the typical compound formulation, it is common for tire rubber to contain 1-2% (weight) of ZnO. ZnO also has appreciable levels of impurities, depending on the raw material and the degree of purification. Even with the French Process, which achieves significant purification based on the vapor pressure differences of metals, Cd and Pb cannot be effectively removed.[9] ZnO of 99.5 and 99% purities produced in China, which is by far the dominant supplier, contains up to 0.12 and 0.2% of PbO, and 0.02 and 0.05% CdO, respectively.[10] ZnO products of lower grades are expected to contain even higher levels of these impurities.

Highly aromatic (HA) oils, also known as distillate aromatic extract oils, are products of oil refining that consist of aromatic and polycyclic aromatic hydrocarbons, and naphthenic and paraffinic hydrocarbons. HA oils are added as extender oils or softeners in the manufacturing process to reduce the cost of tire production by substituting for parts of the more expensive rubber material, make the rubber polymers easier to work, and improve the wet grip, wear resistance, and durability of the tire treads. HA oils typically constitute 10-20% of the stock formula of tires, with truck tires, which operate under more demanding physical conditions, containing lower amounts compared to passenger tires.[11] As the fraction of polycyclic aromatic hydrocarbons (PAHs) in HA oils can amount to 10-30%,[12] the contents of PAHs in tire rubber can be significant.

Carbon black, which is industrially manufactured by partial combustion or oxidative pyrolysis of hydrocarbons at high temperatures under controlled conditions, has been used as a reinforcement filler of choice in tire manufacturing for many years. The production of carbon black involves both the formation and destruction of PAHs. It has been observed that up to 98% of the total PAHs contained in the feedstock were destructed in the carbon black manufacturing process, while the PAHs contained in the final products resulted primarily from the pyrolytic process.[13] Processing conditions significantly affected the PAH concentrations in carbon black: higher temperatures resulted in products with lower total PAH contents, but the carcinogenic potency of the PAHs formed was higher.[13] Laboratory analyses indicated that the PAH contents were typically less than 0.1% in most carbon black grades of a major supplier.[14] Carbon black and silica typically account for up to 28% of the tire weight, thus carbon black is also an important source of PAHs in tire rubber.

4. Assumptions of the Life Cycle Assessment (LCA) Studies

The following assumptions were made in the LCA study comparing the greenhouse gas (GHG) emissions of artificial turf and natural grass:[15]

i. Life cycle time frame: 10 years;

ii. Emission factors: the Canadian GHG emissions factors were used whenever relevant and possible, while the emission factors for the components made in the U.S. and Europe were estimated from the corresponding databases;

iii. Field emissions and sequestration of CO_2 by natural grass: the carbon sequestration factor of natural grass was 0.95 tonne Carbon/ha/year, while the GHG emission factor for the maintenance of the artificial turf field was 30% of that of the natural grass field;

iv. Material transportation: the GHG emission factors for on-road transportation were based on Canadian data and related databases;

v. Disposal: the artificial turf field's components would be 100% recycled, and Canadian data were used for estimating the GHG emission factor for plastic recycling.

The following assumptions were made in the LCA study comparing the environmental impacts of three representative artificial turf products with those of natural grass on a multi-purpose recreational sports field:[16]

i. Life cycle time frame: 20 years;

ii. Material transportation: The distances of material transportation to the field were 250 km during installation, and 100 km during the use, maintenance, and disposal of the fields. The materials were transported by trucks with a diesel fuel efficiency of 2.7 MJ/tonne/km;

iii. Field durability: based on the manufacturers' data, the functional lifetimes of the artificial turf fields with Nylon, polyethylene, and 70% polyethylene/30% Nylon fibers were 10, 8, and 9 years, respectively. No turf replacement was required over the lifetime of the natural grass field;

iv. Field emissions and sequestration of CO_2 by natural grass: each 1,000 ft^2 of natural grass sequesters 0.032 tonne of CO_{2e} per year, while this benefit was also offset by emissions to air (N_2O, 1.5% of application) and water (N, 10% of application) associated with the use of nitrogen-based fertilizers.

3. Tables

Table S1 . Summary of the conditions and major findings of s elected toxicity characteristic leaching procedure (TCLP) studies on ground tire rubber and tire chips.

	Zelibor (1991)[17]	Downs et al. (1996)[18]	Al-Tabbaa and Aravinthan (1998)[19]	Khan et al. (2011)[20]
Solids tested	Ground and unground, cured and uncured tire samples that had been chopped into portions of 1 cm or less.	Glass belted tire chips, mixed glass and steel belted tire chips. Their sizes were reduced to pass the 9.5-mm (0.375-in.) sieve. Samples of 100 g of tire particles were subjected to the leaching test.	Tire rubber particles of 2 size groups (l-4 and 4-8 mm). Samples of 100 g of tire particles were subjected to the leaching test.	Tire chips with 4 particle size groups (1"×1", 2"×2", 4"×2", and 6"×2"). Samples of 100 g of tire chips were subjected to the leaching test.
Extraction fluids	0.1 mol/L acetate buffer at a pH of 4.9	0.1 mol/L acetate buffer at pH 4.9	0.1 mol/L acetate buffer at pH=4.9 0.2	0.1 mol/L acetate buffer at pH =4.93±0.05
Liquid/solid ratio	20:1	20:1	20:1	20:1
Duration	The mixture was mixed by rotary agitation at 30 2 rpm for 18 h.	The mixture was rotated on a tumbler at 30 2 rpm for 18 2 h.	The mixture was agitated at 30 rpm for 17 h	The mixture was agitated at 30 rpm for 18 h
Major findings	Most contaminants were detected at trace levels (near method detection limits), which were 10 to 100 times less than the TCLP regulatory limits or maximum contaminant level (MCL) values for drinking water of the U.S. Environmental Protection Agency.	Although Ba, Cd, Cr, and Pb were detected in the leachate, their concentrations were well below the TCLP regulatory limits. None of the organic compounds leached exceeded the TCLP regulatory limits.	The concentrations of Cu ranged from 0.21 to 0.24 mg/L, while those of Ni were 0.56-0.59 mg/L. Other contaminants were not measured.	Concentrations of heavy metals in the tire leachates were 100 to 1000 times lower than the TCLP regulatory limits.

Table S2. List of potential organic contaminants that can be leached from tire rubber and their sources (adapted from ref. 21).

Contaminant	Major sources in tire rubber
Volatile organic compounds	
1,1,1-Trichloroethane	Solvent
Alcohols	Recipe extender
Aldehydes	Dispersing agent
Alkyl benzenes	Copolymer
Benzene	Solvent
Carbon disulfide	Solvent
Heptane	Recipe extender
Hexane	Recipe extender
Ketones	Recipe extender
Methyl ethyl ketone	Solvent
Petroleum naptha	Recipe extender
Styrene	Polymer/monomer
Toluene	Recipe extender
White gasoline	Recipe extender
Xylenes	Recipe extender
Semi-volatiles and other organic compounds	
1,12-Benzoperylene	Highly aromatic oils, carbon black
1,2-Benzanthracene	Highly aromatic oils, carbon black
1,2-Benzopyrene	Highly aromatic oils, carbon black
2-(4-morpholiny1)-benzthiazole	Antioxidant
3,4-Benzopyrene	Highly aromatic oils, carbon black
4H-cyclopenta[def]-phenanthrene	Highly aromatic oils, carbon black
4H-cyclopenta[def]phenanthre-4-one	Highly aromatic oils, carbon black
6-Acetoxy-2,2-dimethyl-m-dioxane	Inside/outside tire spray, carbon black
6H-benzo[cd]pyren-6-one	Highly aromatic oils, carbon black

9,l0-Dimethyl-1,2-Benzanthracene	Highly aromatic oils, carbon black
Acenaphthylene	Highly aromatic oils, carbon black
Alkyl napthalenes	Vulcanizing agent
Alkylene dithiols	Carbon black
Anathrene	Highly aromatic oils, carbon black
Anthanthrene	Highly aromatic oils, carbon black
Anthracene	Highly aromatic oils, Carbon black
Benzofluoranthene	Highly aromatic oils, carbon black
Benzoyl and other peroxides	Vulcanizing agent
Benzo[a]pyrene	Highly aromatic oils, carbon black
Benzo[def]dibenzothiophene	Highly aromatic oils, carbon black
Benzo[def]napthobenzothiophene	Highly aromatic oils, carbon black
Benzo[e]pyrene	Highly aromatic oils, carbon black
Benzo[ghi]fluoranthene	Highly aromatic oils, carbon black
Benzo[ghi]perylene	Highly aromatic oils, carbon black
Benzo[g]dibenzothiophene	Highly aromatic oils, carbon black
Benzo[i]fluoranthene	Highly aromatic oils, carbon black
Benzo[k]fluoranthene	Highly aromatic oils, carbon black
Benzo[mno]fluoranthene	Highly aromatic oils, carbon black
Benzothiazole	Vulcanization accelerator
Benz[a]anthracene	Highly aromatic oils, carbon black
Benz[e]acenaphthylene	Highly aromatic oils, carbon black
Bisthiol acids	Vulcanizing agent
Butadiene oligomers	Polymer/monomer
Cadmium and zinc soaps	Lubricant
Chrysene	Highly aromatic oils, carbon black
Coronene	Highly aromatic oils, carbon black
Cyclopenta[cd]pyrene	Highly aromatic oils, carbon black
Diazoaminobenzenes	Vulcanizing agent

Dibenzothiophene	Highly aromatic oils, carbon black
Dihydrocyclopentapyrene	Highly aromatic oils, carbon black
Dithiocarbamates	Vulcanization accelerator
Esters	Solvent
Fluoranthene	Highly aromatic oils, carbon black
Indeno[l,2,3-cd]pyrene	Highly aromatic oils, carbon black
Napthalene	Highly aromatic oils, carbon black
Naphthalic Anhydride	Highly aromatic oils, carbon black
Nitrogen containing substances	Copolymer
o-Phenylenepyrene	Highly aromatic oils, carbon black
Organic thiola and sulfides	Carbon black
Perylene	Highly aromatic oils, carbon black
Phenalone	Highly aromatic oils, carbon black
Phenanthrene	Highly aromatic oils, carbon black
Phenol	Softener
Poly- and di-nitrobenzenes	Vulcanizing agent
Pyrene	Highly aromatic oils, carbon black
Quinones	Vulcanizing agent
Siloxanes	Inside/outside tire spray
Styrene oligomers	Polymer/monomer
Substituted p-Phenylenediamines	Antioxidant/antiozonant
Sulfur containing organics	Carbon black
Tetraalkylthiuram disulfides	Vulcanizing agent
Thiazoles	Vulcanization accelerator
Thiuram sulfides	Vulcanization accelerator

Table S3. Typical material composition of passenger and truck tires by weight (adapted from ref. 20).

Component	Function	Content (%) Passenger tire	Truck tire
Rubber/elastomers			
Synthetic rubber	A major component	27	14
Natural rubber	A major component	14	27
Reinforcement fillers		28	28
Carbon black	Strengthens the rubber and increases abrasion resistance		
Silica	As an additive in the tread compounds to increase the grip of tires in water and to minimize rolling resistance		
Metal		14-15	14-15
Steel wire	Reinforces the area under the tread, provides puncture resistance, and helps the tire stay flat to make good contact with the road		
Textiles, additives, and others		16-17	16-17
Woven fabric: polyester, nylon, etc.	Provides the shape, houses the inner tube, and serves as the surface on which the rubber tread is vulcanized		
Sulfur and sulfur compounds	As vulcanization agents to improve the strength and durability of tires		
Phenolic resins	Adhesion promoting resins promote bonding of rubber to textile or steel belts; tackifier resins facilitate assembly of the uncured tires; reinforcing resins improve the hardness and modulus of natural rubber and synthetic rubber		
Extender oils: aromatic, naphthenic, paraffinic	Soften the rubber and increase its workability		
Petroleum waxes	As anti-ozonants to minimize cracking in tires by protecting the polymeric back bone of the rubber against ozone		

	attack		
Calcium oxide	Improves the strength and durability of the rubber		
Zinc oxide	Accelerates the vulcanization process and enhances the physical properties of the rubber		
Titanium (IV) oxide	Accelerates the vulcanization process		
Copper (II) oxide	As a bonding agent to help adhesion of the rubber to the steel belts		
Fatty acids	Aid the vulcanization process and enhance the physical properties of rubber		
Average weight		New: 25 lbs; scrap: 20 lbs.	New: 120 lbs; scrap: 100 lbs.

Table S4. Typical chemical composition of tire rubber ash by weight (%).

Component	Typical passenger tire[a]	Typical truck tire[a]	Unspecified tire[b]
Metal oxides			
ZnO	29.3	34.6	25.1
Al_2O_3	17.11	3.65	8.7
TiO_2	10.14	0.13	1
Fe_2O_3	15.04	19.16	9.3
CaO	2.52	2.45	12.9
MgO	0.63	0.76	6.4
Na_2O	0.91	0.61	1.4
K_2O	1	0.9	1.1
Cr_2O_3	0.03	0.029	N/A
PbO	0.03	0.062	N/A
BaO	0.02	0.012	N/A
CdO	N/D	0.001	N/A
Others			
SiO_2	22.96	23.83	26.5
P_2O_5	0.64	0.75	N/A
SO_3	4.2	5.94	1.6
Chlorine	ND	ND	0.1
Fluorine	ND	0.002	N/A

Notes:

N/D — not detected;

N/A — not available (data not reported);

a — data from ref. 20;

b — data from ref. 22.

4. Figure

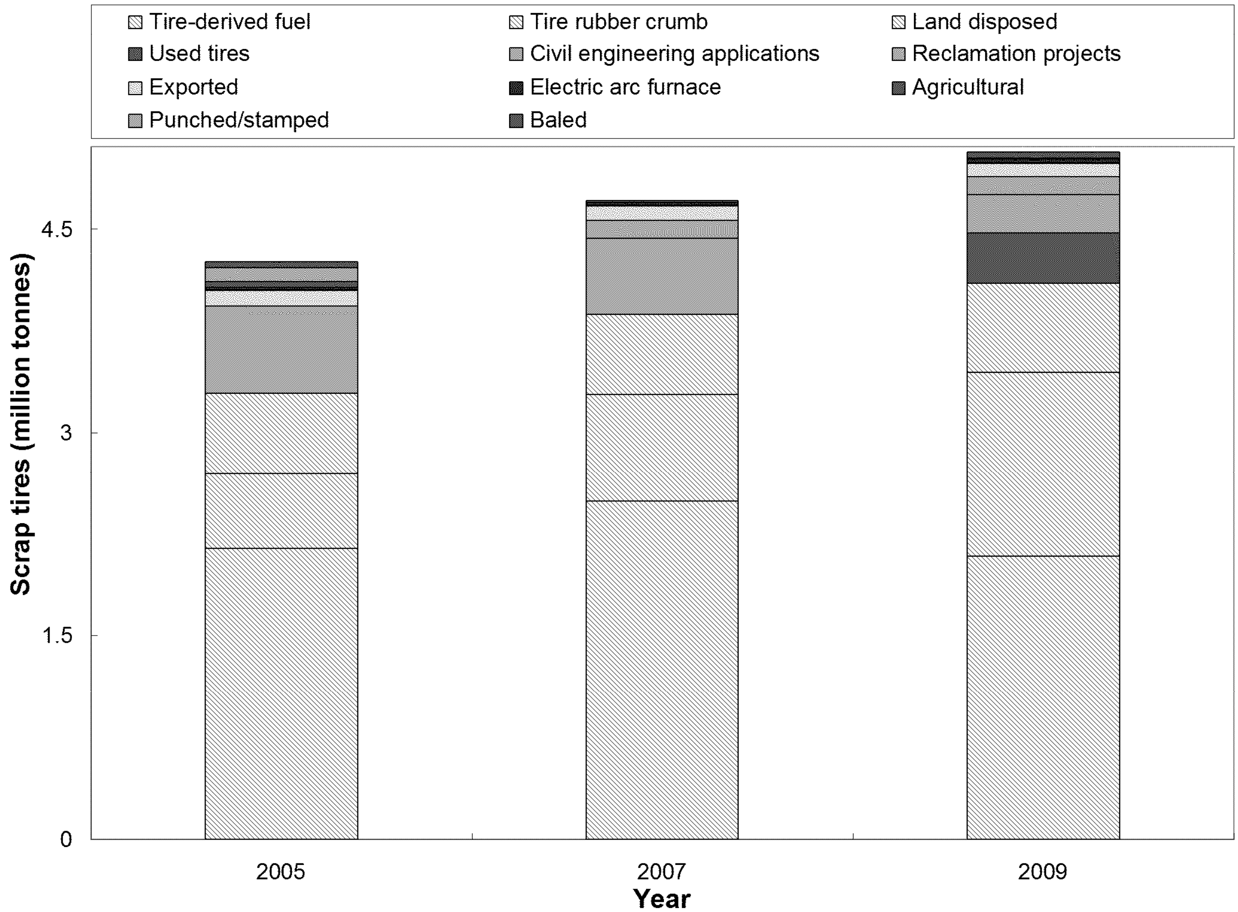

Figure S1. Trend of scrap tire management in the U.S. between 2005 and 2009 (data from ref. 5).

Literature Cited

1. Siddique, R.; Naik, T. R., Properties of concrete containing scrap-tire rubber–an overview. *Waste Manag.* **2004,** *24* (6), 563-569.

2. Fiksel, J.; Bakshi, B. R.; Baral, A.; Guerra, E.; DeQuervain, B., Comparative life cycle assessment of beneficial applications for scrap tires. *Clean Technol. Environ. Policy* **2011,** *13* (1), 19-35.

3. Best, G. A.; Brookes, B. I., Water pollution resulting from a fire at a tire dump. *Environ. Pollut. B Chem. Phys.* **1981,** *2* (1), 59-67.

4. Evans, J. J., Rubber tire leachates in the aquatic environment. *Rev. Environ. Contam. Toxicol.* **1997,** *151*, 67-115.

5. Rubber Manufacturers Association (RMA) *U.S. scrap tire management summary 2005-2009*; Washington, DC, 2011.

6. Smolders, E.; Degryse, F., Fate and effect of zinc from tire debris in soil. *Environ Sci Technol.* **2002,** *36* (17), 3706-3710.

7. Oliphant, K.; Baker, W. E., The use of cryogenically ground rubber tires as a filler in polyolefin blends. *Polym. Eng. Sci.* **1993,** *33* (3), 166-174.

8. Ciullo, P. A.; Hewitt, N., *The Rubber Formulary*. Noyes Publications: Norwich, New York, 1999.

9. International Zinc Association Zinc Oxide Information Center; http://www.znoxide.org/index.html

10. State Bureau of Quality and Technical Supervision, *Zinc Oxide Produced by Direct Method (GB/T 3494-1996)*; Beijing, China, 1996.

11. Rogge, W. F.; Hildemann, L. M.; Mazurek, M. A.; Cass, G. R.; Simoneit, B. R. T., Sources of fine organic aerosol. 3. Road dust, tire debris, and organometallic brake lining dust: roads as sources and sinks. *Environ. Sci. Technol.* **1993,** *27* (9), 1892-1904.

12. Ahlbom, J.; Duus, U. *HA oils in automotive tyres - Prospects of a national ban. KEMI Report No. 5/03*; Swedish National Chemicals Inspectorate: 2003.

13. Tsai, P. J.; Shieh, H. Y.; Hsieh, L. T.; Lee, W. J., The fate of PAHs in the carbon black manufacturing process. *Atmos. Environ.* **2001,** *35* (20), 3495-3501.

14. Cabot Corporation, *Presence of polycyclic aromatic hydrocarbons (PAH) in Cabot carbon black products*; Billerica, MA, 2012.

15. Meil, J.; Bushi, L. *Estimating the required global warming offsets to achieve a carbon neutral synthetic field turf system installation*; Athena Institute: Ontario, Canada, 2007.

16. Uhlman, B.; Diwan, M.; Dobson, M.; Sferrazza, R.; Songer, P. *Synthetic turf, eco-efficiency analysis final report*; BASF Corporation: Florham Park, NJ, 2010.

17. Zelibor, J. L. *The RMA TCLP assessment project: Leachate from tire samples*; Scrap Tire Management Council: 1991.

18. Downs, L. A.; Humphrey, D. N.; Katz, L. E.; Roc k, C. A. *Water quality effects of using tire chips below the groundwater table. Technical Report 94-I*; Department of Civil Environmental Engineering, University of Maine, Orono: 1996.

19. Al-Tabbaa, A.; Aravinthan, T., Natural clay-shr edded tire mixtures as landfill barrier materials. *Waste Manag.* **1998,** *18* (1), 9-16.

20. Khan, A. A.; Karanfil, T.; Selbes, M. *The feasibility of tire chips as a substitute for s tone aggregate in septic tank leach fields, Final report part-II*; Clemson University: 2011.

21. Miller, W. L.; Chadik, P. A. *A study of waste tire leachability in potential dis posal and usage environments: Amended volume 1: Final report*; University of Florida: 1993.

22. Al-Akhras, N. M.; Smadi, M. M., Properties of t ire rubber ash mortar. *Cem. Concr. Compos.* **2004,** *26* (7), 821-826.